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Traffic Control Devices and Measures for Deterring Wrong-Way Movements

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Traffic Control Devices and Measures for Deterring Wrong-Way Movements

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Ann M. Hartell
Staff Officer
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NCHRP Research Report 881 provides an analysis of factors associated with wrong-way movements on unsignalized divided highways and freeways. The divided highway analysis focuses on design, signage, and roadway markings, while the freeway analysis emphasizes the effectiveness of signage with flashing lights. The results are used to identify appropriate countermeasures and to develop specific recommendations for revisions to the *Manual for Uniform Traffic Control Devices* that may deter wrong-way movements by drivers. The report will be of interest to highway design engineers, highway safety researchers, and those responsible for developing design guidance, including the National Committee on Uniform Traffic Control Devices.

Wrong-way movements at entrance ramps and on rural and urban divided highways have resulted in crashes involving serious injuries or deaths for those involved. Although infrequent, the severity and high profile of these crashes has made them a priority for improving highway safety. Yet the *Manual for Uniform Traffic Control Devices* (MUTCD), the Uniform Vehicle Code, and AASHTO's *A Policy on Geometric Design of Highways and Streets* (the "Green Book") provide inconsistent or even conflicting guidance for median width, signage, markings, and other elements for entrance ramps and intersections with approaches to divided highways. Better and more consistent guidance gives designers information on appropriate configurations of traffic control devices and suitable median widths for approaches and ramps to divided highways to deter wrong-way movements and prevent the resulting crashes.

The research was conducted by a consultant team led by the Texas A&M Transportation Institute. The research used crash data involving wrong-way movements from three states to model relationships between traffic control devices and wrong-way movements that resulted in a crash. The analysis focused on (1) determining the type(s), number, and location(s) of traffic control devices required to deter wrong-way movements; and (2) evaluating the impact of varying median widths on wrong-way movement signing and marking requirements on low- and high-speed rural and urban divided highways. The results are interpreted to identify specific needed revisions to the MUTCD that eliminate inconsistencies and conflicting information so as to strengthen the guidance aimed at reducing wrong-way movements.

The report documents the analysis of wrong-way crashes on high-speed rural and urban divided highways. It also includes an analysis of the effectiveness of wrong-way warning signs with flashing lights (LEDs and RFBs), using data from pilot applications of these devices from two states. The report is accompanied by a review of previous research on wrong-way driving, a discussion of relevant sections of the MUTCD, and a detailed set of recommended revisions to the MUTCD.

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SUMMARY

Traffic Control Devices and Measures for Deterring Wrong-Way Movements

In this report, researchers document the results of multiple analyses focused on developing an improved understanding of wrong-way driving crash characteristics on divided highways, as well as wrong-way countermeasure effectiveness on divided highways and freeways. An in-depth safety analysis of wrong-way crashes using a multistate dataset assessed the impact of median width and various traffic control devices upon wrong-way crashes on high-speed divided highways. In addition, wrong-way driving event data were used to evaluate the effectiveness of light-emitting diode (LED) border-illuminated WRONG WAY signs and red rectangular flashing beacons (RFBs) above and below WRONG WAY signs. All of the research findings were then used to develop suggestions for changes to the 2009 *Manual on Uniform Traffic Control Devices* (MUTCD) (2009 MUTCD with Revisions 1 and 2, FHWA 2012).

The findings from this research effort indicate that there is no one traffic control device that can reduce wrong-way movements across all of the circumstances studied (i.e., high-speed rural divided highways, high-speed urban divided highways, and freeways). In addition, the fidelity of the safety analysis did not allow researchers to assess the overall impact of the various combinations of traffic control devices. However, researchers were able to identify several traffic control devices that may be effective in reducing wrong-way movements on high-speed divided highways and freeways. In addition, the research team addressed several inconsistencies with regard to wrong-way movement traffic control in the MUTCD.

There are many factors that impact the operation of a divided highway crossing as one or two intersections. The median width is an important factor, but there are other factors as well. The manner in which the median width, median opening, median design, left-turn movements, and other factors interact could have a significant effect on the potential for wrong-way movements and were beyond the scope of this research project to analyze.

The 30-ft criterion used in the MUTCD and the Uniform Vehicle Code (UVC) to distinguish crossing functions as one or two intersections has existed since at least the mid-1940s. However, there is no known rational basis for the use of 30 ft as the threshold criterion. The safety analysis conducted in this project found that there were numerous sites in the analysis where the traffic control devices did not fully comply with the MUTCD with respect to treating the location as one or two intersections. Primarily, this was represented in narrow medians (less than 30 ft) with STOP or YIELD signs in the median opening (6 percent) or in wide medians (greater than or equal to 30 ft) with no STOP or YIELD signs in the median opening (26 percent). This finding may be an indication that practitioners are using engineering judgment to determine the most effective installation of interior right-of-way devices to address safety and operations at divided highway crossings. There is also evidence from the safety analysis conducted in this project that the criterion may be 50 ft from a safety

perspective. These findings led researchers to suggest changes to the definitions of median width and intersection in the MUTCD.

The safety analysis indicated that most wrong-way movements at divided highway crossings occurred when the driver turned left into the near-side roadway traveling in the wrong direction. The data indicated that this maneuver occurred for 90 percent of the wrong-way crashes for which the wrong-way entry point was specifically identified in crash documentation. Therefore, the suggested changes to the MUTCD language focus upon addressing this maneuver. Additional specific findings from the safety analysis pertinent to the suggested changes to the MUTCD language include the following:

- Greater use of ONE WAY signs (above those that are required) does not appear to deter wrong-way movements.
- There was limited evidence that use of the required divided highway sign on the crossroad exterior approaches deters wrong-way movement.
- The placement of DO NOT ENTER and WRONG WAY signs on the inside turn of a wrong-way movement (side of divided highway nearer the right-of-way line) does not deter wrong-way movements.
- Treatments that appear to deter wrong-way movements include:
  - DO NOT ENTER and WRONG WAY signs on the outside of a wrong-way turn,
  - Wrong-way arrow markings for the through lanes on the divided highway,
  - Presence of a centerline in the median opening, and
  - Use of stop or yield lines when interior right-of-way treatments are provided.

Separate analysis of wrong-way driving event data supported the use of flashing red LEDs within the border of WRONG WAY signs at freeway exit ramps. Therefore, researchers suggest changes to the MUTCD to allow red LEDs within the border of WRONG WAY signs.

Early results from the red RFB WRONG WAY sign system pilot found that most of the errant drivers self-corrected before reaching the main lanes. These promising findings led to additional installations of the red RFB WRONG WAY systems at freeway exit ramps in central Florida. Additional data from these sites are needed before a detailed statistical analysis can be conducted and MUTCD language suggested.

CHAPTER 1

Background

Introduction

Motorists driving the wrong way on divided roadways has been an area of concern for transportation agencies and the traveling public for over 50 years. Even though wrong-way crashes are infrequent, they are a serious problem because such crashes typically result in death or serious injury to the people involved (NTSB 2012). The first wrong-way driving research in the United States occurred in the mid-1960s (e.g., Tamburri 1965; Tamburri and Theobald 1965). A resurgence of wrong-way driving research and countermeasure implementation has taken place over the last decade due to the high-profile nature of these crashes and the FHWA's Toward Zero Deaths vision.

Numerous previous studies have investigated the nature of wrong-way crashes on controlled-access highways (i.e., freeways) (e.g., Moler 2002; NTSB 2012; Baratian-Ghorghi et al. 2014). Most studies have found that these crashes tend to occur more frequently in urban areas, at night, and on the weekend (e.g., Cooner et al. 2004; Zhou et al. 2012; Finley et al. 2014; Kittelson & Associates, Inc. 2015). Many studies have documented the difficulty with identifying the origination of the wrong-way maneuver onto freeways (Cooner et al. 2004; Lathrop et al. 2010; Morena and Leix 2012; Zhou et al. 2012). Even so, a few studies have determined that most wrong-way maneuvers onto freeways originate at exit ramps (Tamburri and Theobald 1965; NTSB 2012). Many studies have also found that wrong-way drivers involved in crashes on freeways tend to be young males and/or driving under the influence of alcohol and/or drugs (e.g., Tamburri and Theobald 1965; Zhou et al. 2012; Baratian-Ghorghi et al. 2014; Finley et al. 2014). In addition, some studies have found that elderly drivers are overrepresented in wrong-way crashes on freeways (NTSB 2012; Baratian-Ghorghi et al. 2014; Kittelson & Associates, Inc. 2015).

Less is known about wrong-way crashes on divided highways because only a few studies have investigated these types of crashes (Tamburri and Theobald 1965; Vaswani 1977; Athey Creek Consultants 2016). Limited data have shown that most wrong-way entries on divided highways occur at intersections with median openings. Other wrong-way entries have occurred when drivers exited business establishments, drove through the median, or made U-turns. A more robust dataset is needed to investigate the characteristics of wrong-way crashes on divided highways and determine the geometric characteristics and traffic control devices that impact their occurrence. Such findings could aid practitioners in the deployment of traffic control devices to deter wrong-way movements on divided highways.

The 2009 *Manual on Uniform Traffic Control Devices* (MUTCD) (2009 MUTCD with Revisions 1 and 2, FHWA 2012) contains information regarding the installation of DO NOT ENTER, WRONG WAY, ONE WAY, and other regulatory signs, as well as pavement markings, to deter wrong-way movements at intersections on divided highways and at exit ramps on freeways. However, inconsistencies between the MUTCD, *Policy on Geometric Design of Highways and Streets* (AASHTO 2011, also known as the Green Book), and state practice have been identified. Transportation agencies are installing active technologies in an effort to further reduce wrong-way movements onto freeways (e.g., Zhou et al. 2012; American Traffic Safety Services Association 2014; Finley et al. 2014; Ponnaluri 2016). Evaluations that help clarify the inconsistencies and assess the effectiveness of active technologies are needed to improve the guidance found in the MUTCD.

Project Objectives

The primary objective of NCHRP Project 03-117 was to examine the characteristics of wrong-way crashes on divided highways and determine the impact of median width and select traffic control devices on their occurrence. A secondary objective was to identify and determine the effectiveness of emerging countermeasures implemented at freeway exit

ramps. To accomplish this, researchers undertook the following major efforts:

- Assessment of data and findings from previous wrong-way driving studies to quantify crash characteristics, identify countermeasures, and assess the effectiveness of countermeasures;
- Comprehensive review of the MUTCD regarding wrong-way movement signing and markings at freeway ramps and non-signalized divided highway crossings;
- Analysis of the effects of median width and traffic control devices upon wrong-way crashes on high-speed rural and urban divided highways using a multistate dataset developed under this research effort;
- Evaluation of the effectiveness of LEDs within the border of WRONG WAY signs and red RFBs above and below WRONG WAY signs at freeway exit ramps; and
- Development of proposed changes to the MUTCD based on the findings of the research.

The detailed results of the efforts regarding the first and second bullets above, as well as the detailed proposed changes to the MUTCD, are located in the appendices. This report specifically addresses the methodology and results of the third and fourth bullets above. Some of the findings from the literature review and review of the MUTCD appear throughout the report as specific topics are discussed.

Definitions

Throughout this report, the term "freeway" refers to a multilane highway with fully controlled access (i.e., vehicles can only enter and exit at designated ramps). The term "divided highway" refers to a multilane, non-freeway facility where the opposing travel directions are separated by a median. Divided highways typically have at-grade intersections and no control of access between intersections (i.e., direct driveway access allowed). Divided highways do not include roadways with continuous, two-way left-turn lanes.

In this study, the median width was defined as the area between the inside edge of the traveled way of the near travel lane or left-turn lane, if present, to the inside edge of the traveled way of the opposing through lane. This measurement included the inside shoulders, but not left-turn lanes. This definition matches the one used in the MUTCD in order to correlate interactions between the median width and traffic control devices. The medians were either raised (i.e., curb) or depressed (i.e., landscape).

High-speed divided highways had a posted speed limit greater than or equal to 50 mph, and low-speed divided highways had a posted speed limit less than or equal to 45 mph. These definitions are consistent with the Green Book (AASHTO 2011), the Texas *Roadway Design Manual* (Texas DOT 2014), the *Manual on Uniform Standards for Design, Construction, and Maintenance for Streets and Highways* (Florida DOT 2013), and the California *Highway Design Manual* (Caltrans 2016).

Urban areas were defined as those having a population of 5000 or more. Rural areas were outside the boundaries of urban areas and had a population less than 5000. These definitions are consistent with the Green Book, the Texas DOT Crash Records Information System (CRIS), and the *RCI [Roadway Characteristics Inventory] Features and Characteristics Handbook* (Florida DOT 2014).

Contents of This Report

This technical report documents the methodology and results of the various research activities performed in this project. Following this introductory chapter, Chapter 2 presents the data, methodology, and results of the analysis of wrong-way driving crashes on high-speed rural and urban divided highways correlated to median width and traffic control devices. Chapter 3 then presents the data, methodology, and results of two separate analyses conducted to determine the effectiveness of LEDs within the border of WRONG WAY signs and RFBs above and below WRONG WAY signs at freeway exit ramps. Finally, Chapter 4 presents a summary of the key findings from these efforts and provides an overview of the suggested changes to the MUTCD. Appendix A contains a summary of the domestic and international research reviewed. Appendix B provides an overview of the applicable MUTCD sections and figures, as well as other pertinent documents. Appendix C contains the detailed suggested revisions to the 2009 MUTCD (FHWA 2012).

CHAPTER 2

Divided Highway Crash Analysis

This chapter provides information regarding the methodologies used to develop a divided highway multistate crash dataset. This dataset was used to determine the characteristics of wrong-way crashes and wrong-way drivers. The dataset was also used to analyze the effects of geometric features and traffic control devices upon wrong-way crashes on high-speed rural and urban divided highways.

Divided Highway Multistate Crash Dataset

In order to assess the characteristics of wrong-way crashes on divided highways and determine the effects of multiple design features and traffic control devices upon wrong-way crashes on divided highways, the research team compiled a multistate crash dataset. A recent analysis of wrong-way fatal crashes in the United States (Baratian-Ghorghi et al. 2014) found that the states with the highest number of wrong-way fatal crashes and fatalities were Texas (14 percent), California (10 percent), and Florida (8 percent) (based on the Fatality Analysis Reporting System data from 2004 to 2011). These three states also provided geographic representation from the western, central, and eastern United States.

The following sections detail the data obtained from each state and the methodology used to identify the wrong-way crashes, wrong-way crash corridors, and control corridors. Preliminary descriptive statistics revealed that wrong-way crashes rarely occur on low-speed, rural divided highways (1 percent). In addition, researchers conducted a preliminary statistical analysis of the severity of the wrong-way crashes in Texas and Florida by location (urban and rural) and speed limit. In Texas, researchers found that the probability of a severe outcome (i.e., KAB crash) increased with increasing speed limit. In addition, the probability of a severe outcome at lower speed limits (less than 50 mph) was less than 25 percent. Although speed limit was not found to be a statistically significant variable in the Florida model selection process, the trend was comparable to that found for Texas. Based on these findings and the project panel's input, the research team limited the divided highway crash analysis to high-speed (≥ 50 mph) roadways.

Wrong-Way Crash Corridors

Texas

The research team obtained crash data for 2012 to 2014 from CRIS. Only crashes that occurred on Texas DOT roadways and resulted in injury, death, or at least $1000 in damage were included in the dataset. Researchers used the contributing factor variable to identify wrong-way-related crashes. CRIS lists up to three contributing factors and up to two possible contributing factors for each crash (up to five overall). A contributing factor code of 69 represents "wrong side—approach or intersection," 70 represents "wrong side—not passing," and 71 represents "wrong-way—one-way road." Researchers included all three codes in order to capture all possible wrong-way crashes. Initially, the research team identified 2751 wrong-way crashes.

Researchers then used the speed limit, road type, and functional system variables to reduce the dataset. The speed limit variable was used to retain wrong-way crashes that occurred on high-speed roadways. The road type variable was used to remove two-lane, two-way roadways and undivided roadways. While the functional system code included categories for urban and rural interstates, as well as other urban freeways, it did not include a category for divided highways. Furthermore, a cursory review of the wrong-way crashes coded as occurring on an interstate or other urban freeway revealed that the functional system for some of these crashes was miscoded. Therefore, the research team decided to plot all the crashes using the geolocation information (i.e., latitude and longitude) and manually determine the type of roadway for each crash. Using the verified location information, the

research team found that 255 wrong-way crashes occurred on high-speed divided highways.

Next, researchers reviewed the crash diagrams and associated narratives for the wrong-way driving crashes that occurred on high-speed divided highways. Based on this review, 54 crashes (20 percent) were removed because they were determined not to be wrong-way crashes of interest. Many of these crashes were the result of a right-way driver losing control of his or her vehicle and ending up on the wrong side of the road. Researchers expected this might occur because Texas uses multiple codes to flag wrong-way driving as a contributing factor. All of these codes were initially included in the dataset to ensure that no crashes of interest were excluded.

The crash diagrams and associated narratives only mentioned specific entry points for 32 of the 201 (16 percent) remaining wrong-way crashes. Using these limited data, the research team determined that the average wrong-way entry occurred within 777 ft (0.15 mi) of the crash with a standard deviation of 972 ft. Given these characteristics, it can be easily shown that most of the wrong-way entries were within 2682 ft (0.51 mi) of the crash and 41 percent of these crashes originated at T-intersections where a crossover to the opposite travel direction was provided. Based on these findings, the research team decided to create study corridors 1 mi in length (0.5 mi in each direction from the crash). The research team developed a process by which staff identified the study corridors surrounding the wrong-way crashes in Google Earth. The most likely wrong-way entry points were determined using crash data elements (e.g., direction of travel, side of road), crash diagrams (only available for Texas data), and engineering judgment. The corridor length was extended, as needed, to include the most likely wrong-way entry point or to accommodate multiple crashes. Researchers then used Google Earth to obtain various characteristics of the most likely wrong-way entry point (e.g., various cross-section measurements, median type, intersection type, interior and exterior traffic control devices present, lighting presence, and speed limit). A review of the traffic control devices present at each probable wrong-way entry point revealed that 18 locations were signalized intersections. The research team removed these sites from the dataset since the focus of this research was wrong-way movements at unsignalized intersections. Overall, the final Texas dataset contained 183 wrong-way crashes on high-speed divided highways (117 rural and 66 urban) and 168 study corridors (111 rural and 57 urban). Thirteen corridors contained multiple crashes.

Florida

The research team obtained the 2010 to 2013 crash point shape files from Florida DOT. These files contained crashes that occurred on the state highway system and involved:

- Death, personal injury, or indication of pain of persons involved in the crash;
- Leaving the scene involving damage to attended vehicles or property;
- Driving while under the influence; and
- A vehicle inoperable to a degree that required a wrecker or involved a commercial vehicle.

The research team used the two-digit code that gives driver actions at the time of the crash to determine which crashes for each year were attributed to a wrong-way driver (i.e., 21—wrong side or wrong way). Additionally, the research team used the road category variable to determine the following for wrong-way crashes:

- Type of roadway—freeway, divided roadway, or other;
- Area type—urban, suburban, or rural; and
- Other descriptors (e.g., interstate, ramp).

Similar to the Texas dataset, the Florida dataset did not include a variable that specifically separated divided highways from other types of divided roadways. Therefore, the research team again used geolocation information (i.e., latitude and longitude) to plot each crash and visually confirm the type of roadway.

Using a similar process, researchers identified the study corridors and most likely wrong-way entry points for the Florida wrong-way crashes. In addition, the signalized intersection wrong-way entry points and the associated crashes were removed from the dataset. The final high-speed divided highway dataset for Florida included 160 wrong-way crashes (59 rural and 101 urban) and 142 study corridors (48 rural and 94 urban). Thirteen corridors contained multiple crashes.

California

The research team reduced and analyzed the California dataset (2008–2011) received from the Highway Safety Information System (HSIS). This dataset contains crashes investigated by the California Highway Patrol that result in injury, death, or at least $500 in damage. The research team used the two-digit code that gives the collision factor category of the crash to determine which crashes for each year were attributed to a wrong-way driver (i.e., 05—wrong side of road). The research team then used the divided highway variable to determine whether the roadway was divided or not. Next, the research team used the roadway classification variable in the roadway file to determine the type of roadway (i.e., limited access or divided non-freeway) and whether the roadway was urban or rural. The research team then removed all roadways with fewer than four lanes using the total number of lanes variable. Finally, the research team used the median

type variable to remove divided non-freeway facilities with two-way left-turn lanes or other miscellaneous median lanes (e.g., bus lanes).

Similar to the Texas and Florida datasets, the variables in the California dataset did not separate divided highways from other types of divided roadways. However, the California dataset also did not include geolocation information (i.e., latitude and longitude). Using other variables and California roadway information, the research team successfully identified the location of the California divided highway wrong-way crashes to within 1/10 of a mile and then plotted the crash locations using ArcGIS. Researchers then identified the study corridors and most likely wrong-way entry points for the California wrong-way crash data on high-speed divided highways. Wrong-way entry points at signalized intersections and their associated crashes were removed from the dataset. Overall, the final California dataset contained 66 wrong-way crashes (38 rural and 28 urban) and 48 study corridors (27 rural and 21 urban) on high-speed divided highways. Fifteen corridors contained multiple crashes.

Summary

Table 1 provides a summary of the high-speed divided highway wrong-way crash dataset. Overall, the research team verified 409 wrong-way crashes on high-speed divided highways that were the result of wrong-way entries from unsignalized intersections. Fifty-two percent of these crashes occurred in rural areas, while the other 48 percent happened in urban areas. These crashes occurred in 358 corridors that were identified by researchers using previously described methods. Because multiple crashes occurred in some of the selected corridors, the number of crash corridors was less than the number of wrong-way crashes.

Control Corridors

In order to avoid biasing the results by just focusing on sites with a reported history of wrong-way crashes, the research team wanted to supplement the dataset with data from sites with no recorded wrong-way crashes. In order to achieve this goal, the research team developed a procedure to draw statistically representative site samples from the three states under study.

The research team used the roadway inventory files from each of the three states under study as sampling frames in order to perform the probability sampling of control corridors. However, the research team needed to ensure that segments with a wrong-way crash history were avoided and that no overlap of crash segments and control segments occurred. Therefore, the research team developed a 2-mi buffer around the segments with previously identified wrong-way crashes and removed those segments from the sampling frame.

After excluding the segments in close proximity to each identified wrong-way crash, the research team applied filters to identify urban and rural sites with speed limits greater than or equal to 50 mph, and with at least four through lanes (two lanes per direction). Using the three reduced roadway inventories as sampling frames, the research team utilized an open source software environment and package (Fox and Weisberg 2011; R Development Core Team 2011) to draw a random subset of roadway sections intended to identify candidate control corridors.

In the cases of Texas and Florida, the filters to identify high-speed multilane highways could be applied with relative ease because the road inventories for these two states had all the required variables. However, for California, this task was especially challenging because the roadway inventory was obtained from the HSIS, and that database does not offer any geodesic information. Initially, the research team attempted to use an unfiltered sample of California segments to identify control sections. However, this sample required a large amount of effort to identify segments with the required characteristics, yielding very few actual control sites.

The complication with lack of geodesic information in the California data had emerged earlier, when the research team determined the segments with wrong-way crashes. To overcome this issue, the research team estimated the approximate geolocation of the crashes by matching the linear referencing fields from the HSIS crash table to the corresponding linear referencing fields in a shape file obtained from Caltrans. This

Table 1. Overview of high-speed divided highway wrong-way crash dataset.

Data	Texas	Florida	California	Overall
Number (%) of Wrong-Way Crashes				
Urban	66 (36%)	101 (63%)	28 (42%)	195 (48%)
Rural	117 (64%)	59 (37%)	38 (58%)	214 (52%)
Total	183 (45%)	160 (39%)	66 (16%)	409 (100%)
Number of Wrong-Way Corridors				
Urban	57	94	21	172
Rural	111	48	27	186
Total	168	142	48	358

Table 2. Summary of control corridors.

State	Number of Rural	Number of Urban	Total
Texas	65	57	122
Florida	44	93	137
California	42	7	49
Total	151	157	308

shape file consists of geolocation markers every 1/10 of a mile along California highways. Similar to the instance of defining segments with wrong-way crashes, the research team performed an analysis to match the HSIS road inventory table to the referenced shape file. Additional sample road segments were obtained from the matched databases and were subsequently used to define California control segments.

Table 2 contains a summary of the identified control corridors for each state and overall. The more labor-intensive selection process for California resulted in fewer control sites compared to Texas and Florida. However, the number of control sites for each state was similar to the number of crash corridors for each state. For each control corridor, researchers randomly chose an unsignalized intersection with a median opening and documented its characteristics (e.g., various cross-section measurements, median type, intersection type, interior and exterior traffic control devices present, lighting presence, and speed limit).

Wrong-Way Crash Characteristics

Before performing the statistical analysis, the research team conducted an exploratory analysis of the wrong-way crash data to examine trends. Table 3 shows the percentage of wrong-way crashes by crash severity. The Texas and Florida dataset were very similar, with most of the wrong-way crashes on high-speed divided highways resulting in a serious injury. In contrast, almost 68 percent of the wrong-way crashes on high-speed divided highways in California resulted in possible injuries or property damage only. Overall, 54 percent of the wrong-way crashes on high-speed divided highways resulted in serious injuries.

Figure 1 shows the trends for wrong-way crashes on high-speed divided highways by day of the week for each state and overall. The Texas and Florida data exhibited similar characteristics by day of the week. For California, the research team identified a larger amount of wrong-way crashes on Tuesday and Friday and fewer wrong-way crashes on Saturday. Even so, overall, most of the wrong-way crashes on high-speed divided highways occurred on Friday, Saturday, and Sunday (53 percent).

Table 4 contains the percentage of wrong-way crashes on high-speed divided highways by lighting condition. Again, the Texas and Florida datasets were very similar, with about two-thirds of the wrong-way crashes occurring at night. In contrast, more than half of the California wrong-way crashes occurred during the day. Even so, overall, most of the crashes on high-speed divided highways occurred at night.

Based on a review of the Texas crash diagrams, crash descriptors (e.g., vehicle direction and side of the roadway), and engineering judgment, the research team identified the most likely wrong-way entry point in each crash corridor in each state. Table 5 shows the types of intersections from which drivers presumably entered divided highways and went the wrong direction by state and overall. In some locations, the divided highway would intersect with another major roadway and entrance/exit ramps were used to connect the two major roadways, leading to 8 percent of the wrong-way entries. In other situations, the driver crossed through the median (less than 1 percent) or median opening (7 percent) and began to drive in the wrong direction on the other side of the road. Entries from private driveways (e.g., individual homes/subdivisions and businesses), three-leg intersections, and four-leg intersections accounted for 7 percent, 49 percent, and 29 percent of the wrong-way entries, respectively. More than two-thirds of the wrong-way entries from intersecting roadways occurred where median openings were present. These wrong-way entries at median openings resulted in

Table 3. Percentage of wrong-way crashes by crash severity.

State	KAB	CO	Unknown
Texas (n = 183)	60%	39%	1%
Florida (n = 160)	57%	42%	1%
California (n = 66)	32%	68%	0%
Total (n = 409)	54%	45%	1%

Note: KAB = Killed, incapacitating injury, and non-incapacitating injury; CO = Possible injury and not injured (property damage only).

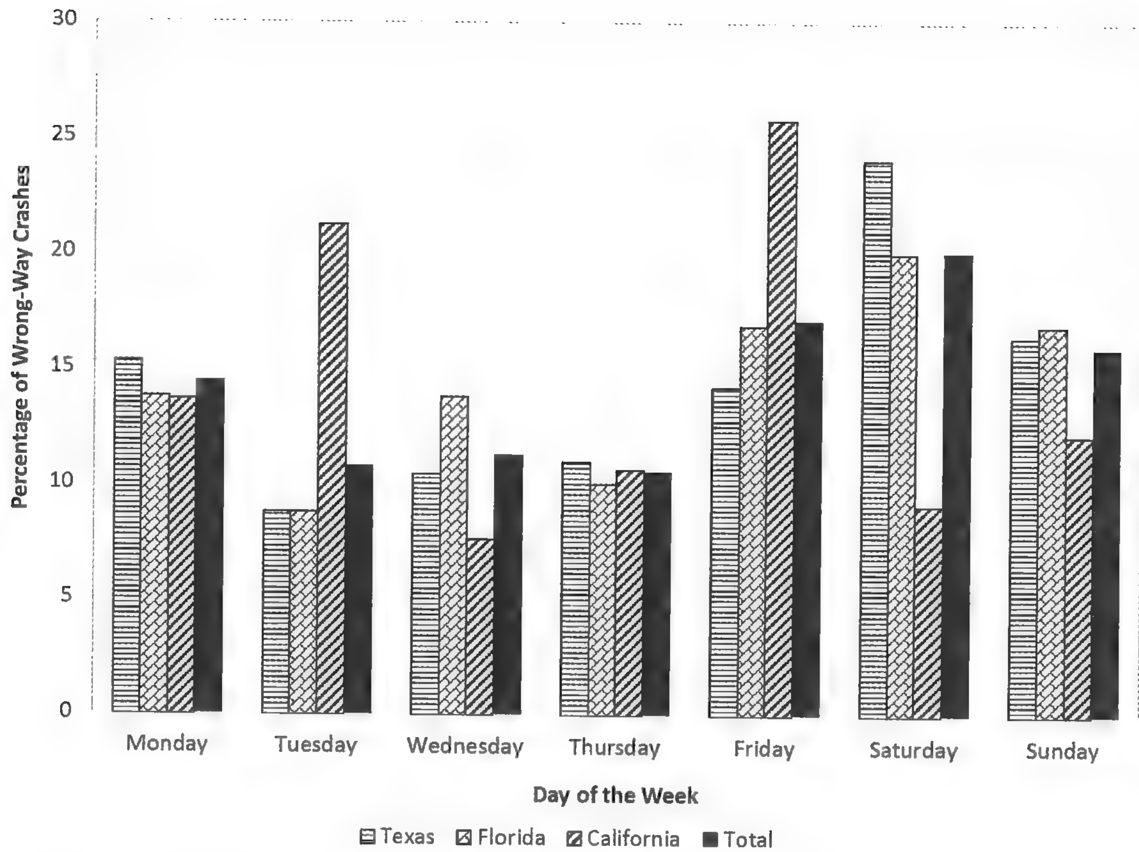


Figure 1. Percentage of wrong-way crashes by day of the week.

Table 4. Percentage of wrong-way crashes by lighting condition.

State	Daylight	Dawn/Dusk	Night
Texas (n = 183)	32%	3%	65%
Florida (n = 160)	30%	2%	68%
California (n = 66)	54%	8%	38%
Total (n = 409)	35%	3%	62%

Table 5. Intersection type at most likely wrong-way entry points by state and overall.

Intersection Type	Texas (n = 183)	Florida (n = 160)	California (n = 66)	Overall (n = 409)
Ramp	22 (12%)	3 (2%)	9 (13%)	34 (8%)
Crossed median	2 (1%)	0 (0%)	0 (0%)	2 (<1%)
Median opening only	14 (8%)	11 (7%)	3 (5%)	28 (7%)
Private driveway				
With median opening	10 (5%)	0 (0%)	2 (3%)	12 (3%)
Without median opening	11 (6%)	1 (<1%)	3 (5%)	15 (4%)
Total	21 (11%)	1 (<1%)	5 (8%)	27 (7%)
Three-leg intersection				
With median opening	64 (35%)	66 (41%)	16 (24%)	146 (36%)
Without median opening	9 (5%)	38 (24%)	6 (9%)	53 (13%)
Total	73 (40%)	104 (65%)	22 (33%)	199 (49%)
Four-leg intersection with median opening	51 (28%)	41 (26%)	27 (41%)	119 (29%)

75 percent of the wrong-way crashes that occurred on high-speed divided highways with four lanes (two in each direction) and a grass median.

Table 6 shows the intersection type from which the wrong-way movement most likely occurred by area type (i.e., rural and urban). The most notable differences were found for ramps, three-legged intersections, and four-legged intersections. In rural areas, slightly more wrong-way entries initiated at three-legged intersections with median openings and four-legged intersections. In urban areas, more wrong-way entries were attributed to ramps and three-legged intersections without median openings.

Based on a subset of the Texas crash data for which the crash diagrams and associated narratives mentioned specific entry points (n = 32), researchers found that 63 percent entered via at-grade intersections. Ninety percent of the wrong-way entries from at-grade intersections occurred when a driver turned left from an intersecting roadway into the near main lanes. The remaining 10 percent of the wrong-way maneuvers occurred when a driver crossed the near main lanes but then turned right into the far main lanes. In one of these occurrences, the wrong-way driver was trying to enter a business driveway that was located to the right of the median opening. In the other case, the geometry of the intersection did not allow drivers on the minor approach to enter the near main lanes (i.e., near main lanes went over minor approach with no ramp). The wrong-way driver crossed under the near main lanes and then turned right into the far main lanes (at-grade intersection). These data are similar to those found in Iowa (Athey Creek Consultants 2016).

Figure 2 shows the median width at the assumed wrong-way entry points at intersections with a median opening by state. The median width depicted was measured from the edge of the traveled way to the edge of the traveled way and included shoulders but not turn lanes (i.e., MUTCD definition). This figure shows that most of the median widths were less than 100 ft.

According to the MUTCD, for median widths less than 30 ft, no control is needed on the interior approaches in the median. For median widths 30 ft or wider, the interior approaches in the median should be controlled with a STOP or YIELD sign. For wrong-way entries at intersections with median openings, researchers found that 18 percent of the sites had median widths less than 30 ft and 82 percent of the sites had median widths 30 ft or wider.

Figure 3 shows the type of control in the median opening (i.e., none, STOP sign, or YIELD sign) at the presumed wrong-way entry points by median width. No control was found at 110 (40 percent) of the wrong-way entry points with median widths that ranged from 3 to 241 ft. Seventy-two percent of the locations without control had median widths greater than 30 ft (denoted by line). All but three of these locations had median widths from 30 ft to 80 ft wide. The research team did verify with Google Earth that the larger median width values did not have any control in the median opening.

STOP or YIELD signs were found in the median opening at 47 (17 percent) and 117 (43 percent) of the wrong-way entry points, respectively. Twelve percent of these locations had median widths less than 30 ft.

Wrong-Way Driver Characteristics

The research team also explored the characteristics of the wrong-way drivers involved in crashes on high-speed divided highways. This analysis only included data from Texas and Florida. There was no way to determine the at-fault driver from the California occupant data obtained from HSIS.

Figure 4 shows the gender of the wrong-way drivers by state and overall. In all cases, females represented about one-third

Table 6. Intersection type at most likely wrong-way entry points by area type.

Intersection Type	Rural (n = 213)	Urban (n = 196)	Overall (n = 409)
Ramp	10 (5%)	24 (12%)	34 (8%)
Crossed median	2 (1%)	0 (0%)	2 (<1%)
Median opening only	17 (8%)	11 (6%)	28 (7%)
Private driveway			
With median opening	11 (5%)	1 (1%)	12 (3%)
Without median opening	7 (3%)	8 (4%)	15 (4%)
Total	18 (8%)	9 (5%)	27 (7%)
Three-leg intersection			
With median opening	85 (40%)	61 (31%)	146 (36%)
Without median opening	7 (3%)	46 (23%)	53 (13%)
Total	92 (43%)	107 (54%)	199 (49%)
Four-leg intersection with median opening	74 (35%)	45 (23%)	119 (29%)

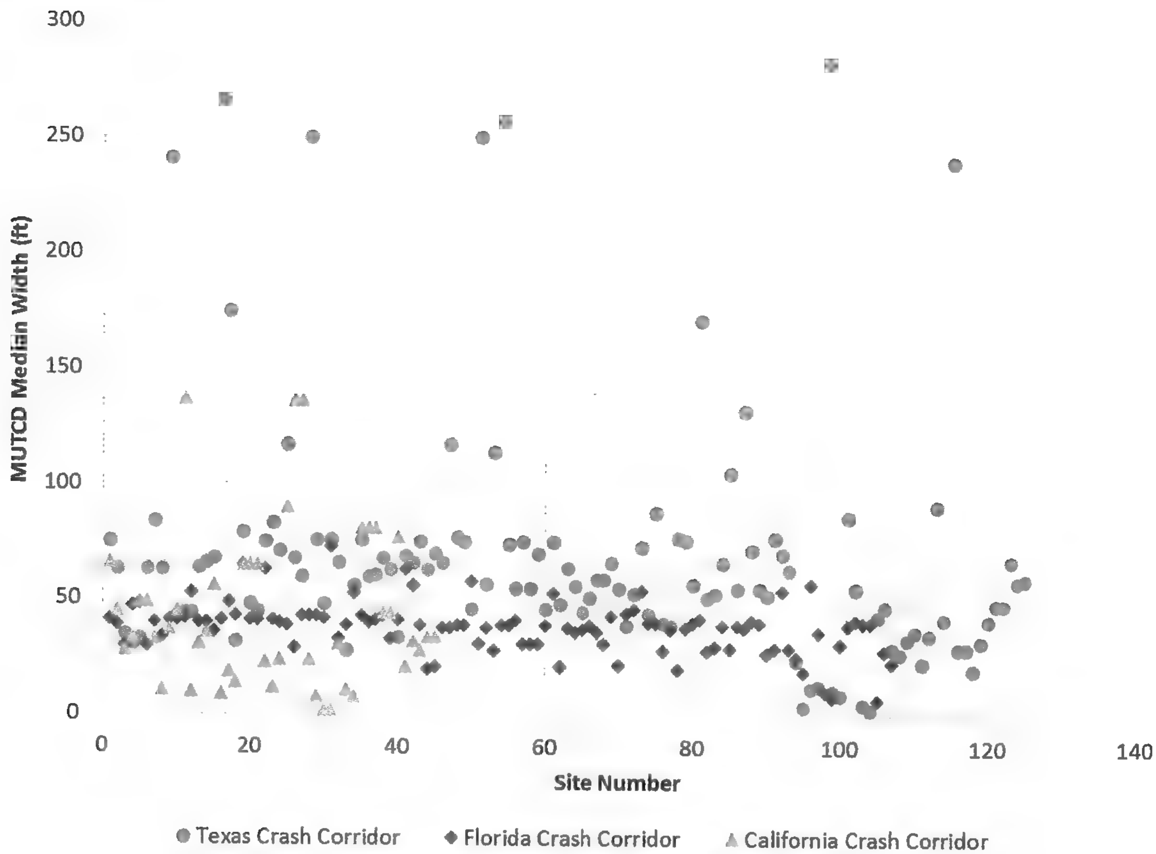


Figure 2. MUTCD median width at wrong-way entry points with median openings by state (n = 277).

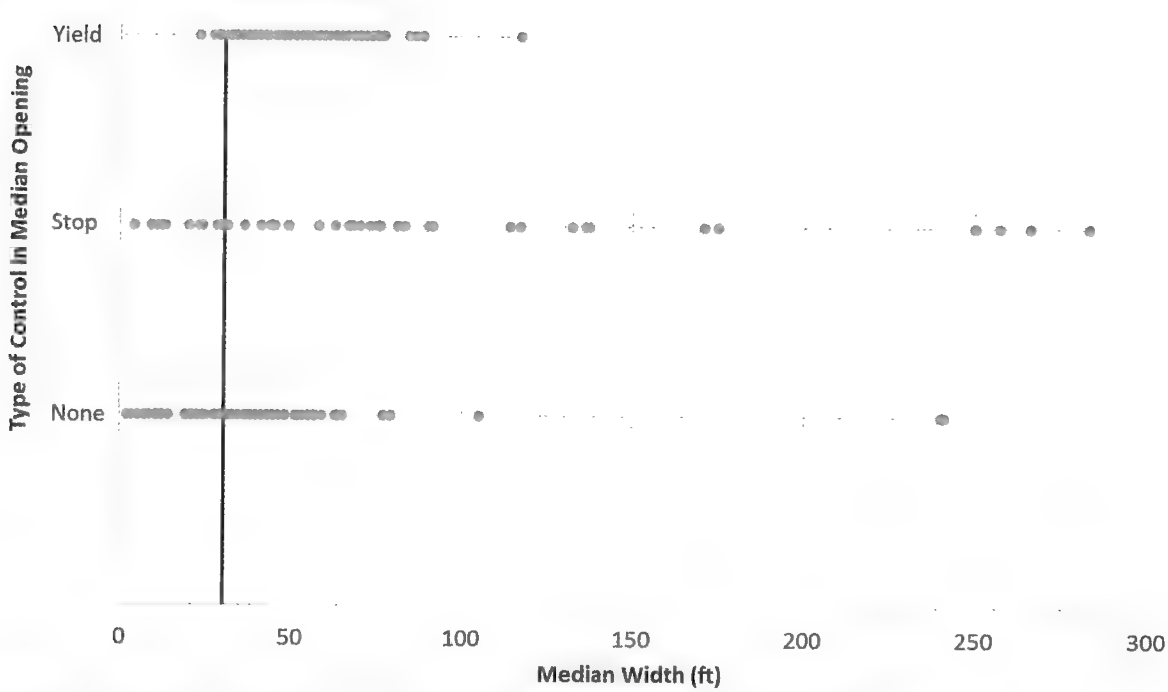


Figure 3. MUTCD median width by type of control in the median for wrong-way entry points with median openings (n = 277).

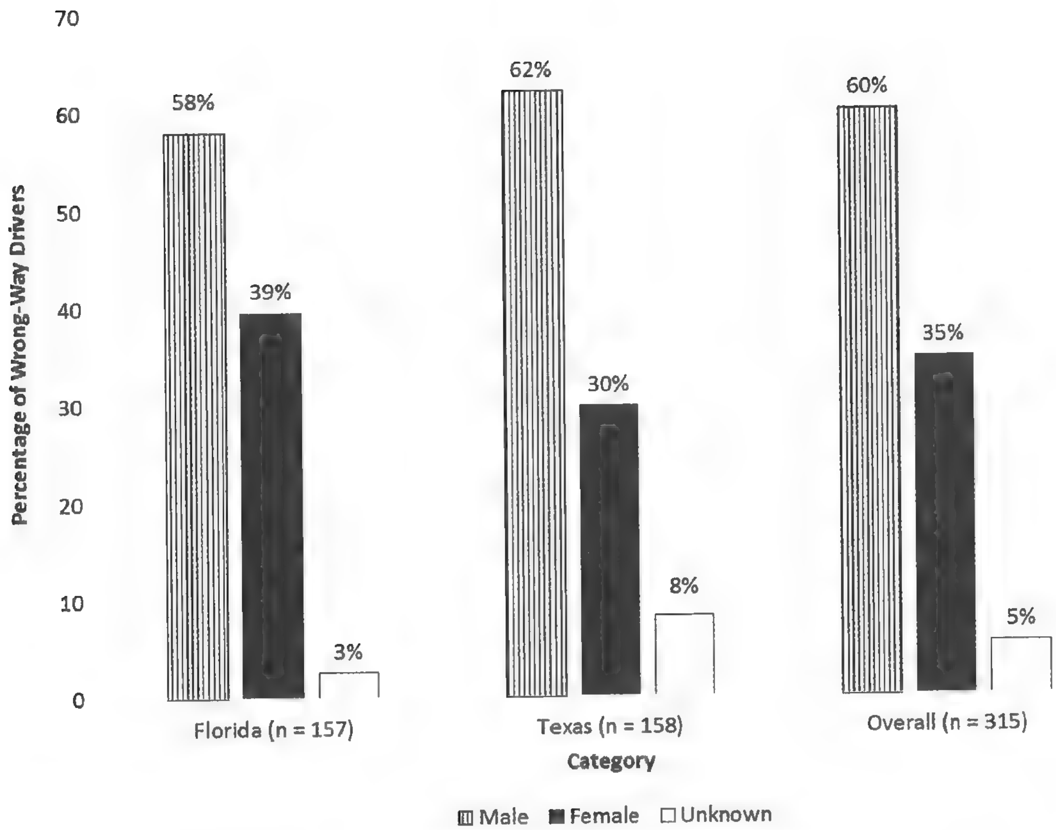


Figure 4. Gender of wrong-way drivers on high-speed divided highways by state and overall.

of the wrong-way drivers, while males represented two-thirds of the wrong-way drivers.

Figure 5 shows the age of the wrong-way drivers on high-speed divided highways by state and overall. In Florida, older drivers (≥ 60) represented 32 percent of the wrong-way drivers, and those ages 21 to 29 accounted for 29 percent. In contrast, in Texas, older drivers accounted for only 16 percent of the wrong-way drivers. The largest portion of Texas wrong-way drivers were ages 21 to 29. The three middle-age categories were relatively consistent between the two states and overall. Table 7 shows that most of the wrong-way drivers, independent of age, made wrong-way maneuvers on high-speed divided highways that led to crashes at night.

Figure 6 shows the cumulative distribution of the blood alcohol concentration (BAC) levels for the 67 wrong-way drivers from both states that tested positive for alcohol. For the remaining 248 wrong-way drivers, either the driver tested negative for alcohol (n = 126, or 40 percent) or the entry was blank (n = 122, or 39 percent). Key findings from Figure 6 include:

- More than 90 percent had a BAC level equal to or greater than the legal limit (0.08 g/dL).
- Almost 70 percent had a BAC level equal to or greater than twice the legal limit (0.16 g/dL).
- Almost 25 percent had a BAC level equal to or greater than three times the legal limit (0.24 g/dL).

Statistical Modeling

In addition to the exploratory analysis, the research team worked to develop models that could be used to explore the relationships with potential explanatory variables as changes in the odds of a wrong-way crash occurring.

Overview of Statistical Analyses

Initially, the research team proposed using the proportion of wrong-way crashes among all crashes in a study site as the response variable to analyze. This approach is applicable in situations where the dataset is collected either by using a random process to assure representativeness or by selecting a range or combination of independent variables under evaluation. However, in this effort, the dataset was compiled from two subsets: one of sites with a known history of wrong-way crashes and one of random sites with

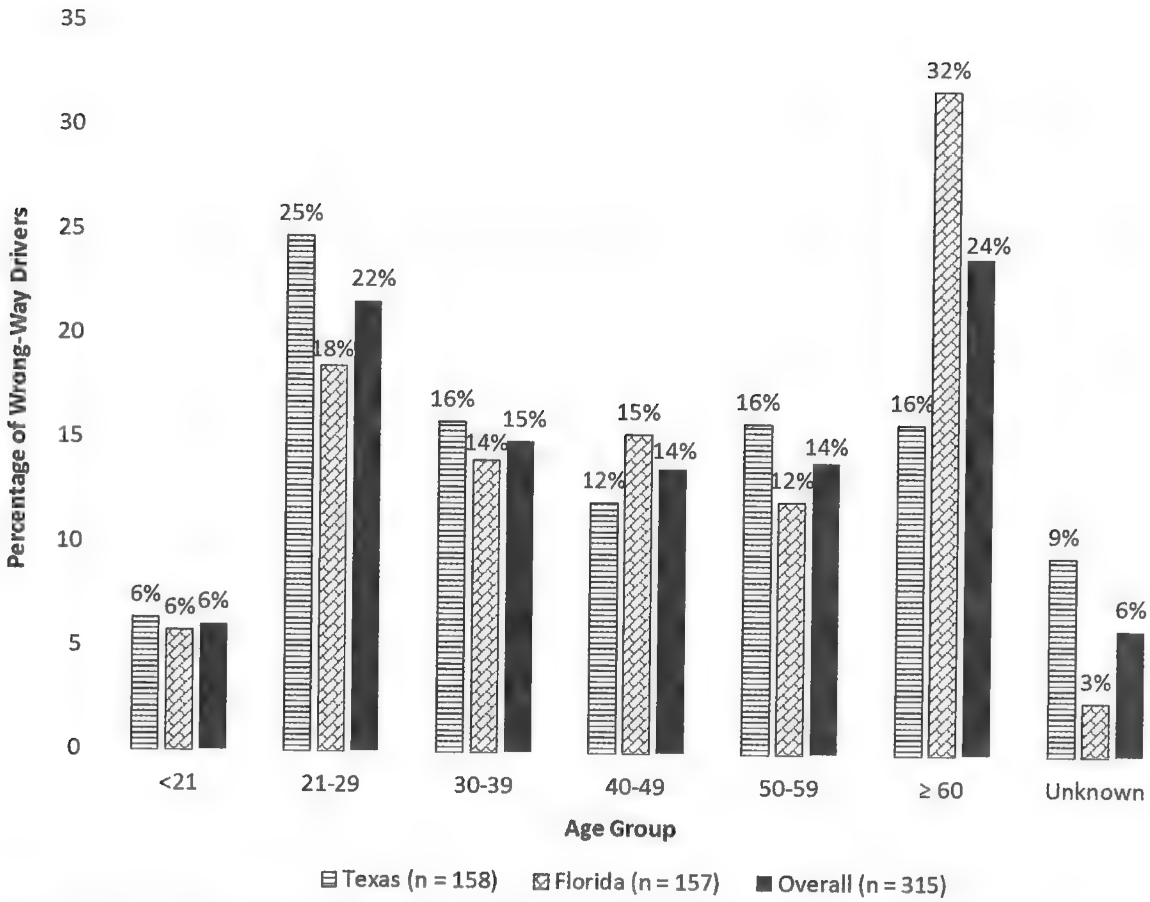


Figure 5. Age of wrong-way drivers on high-speed divided highways by state and overall.

Table 7. Wrong-way driver age versus time of day.

Age Group	Florida (n = 157)		Texas (n = 158)		Overall (n = 315)	
	Day (n = 47)	Night (n = 110)	Day (n = 52)	Night (n = 106)	Day (n = 99)	Night (n = 216)
< 21	11%	89%	50%	50%	32%	68%
21–29	24%	76%	23%	77%	24%	76%
30–39	18%	82%	20%	80%	19%	81%
40–49	25%	75%	32%	68%	28%	72%
50–59	37%	63%	40%	60%	39%	61%
≥ 60	38%	62%	44%	56%	40%	60%
Unknown	75%	25%	40%	60%	47%	53%
Total	30%	70%	33%	67%	31%	69%

Note: Shading indicates majority of the crashes.

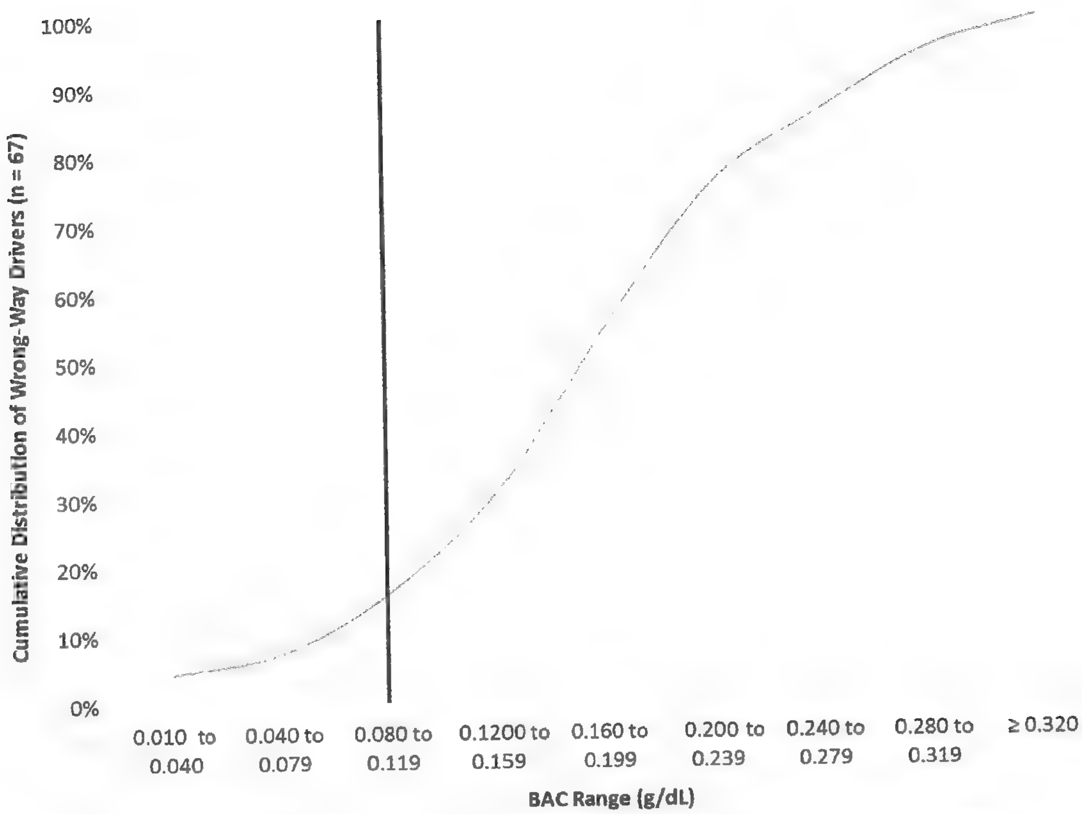


Figure 6. Cumulative distribution of BAC levels for wrong-way drivers involved in a crash on high-speed divided highways.

no history of wrong-way crashes. Because of the different approach to developing the dataset, the method of analysis was modified slightly. Instead of using the proportion of wrong-way crashes as the response variable, the final method of analysis defined the response variable as the probability of wrong-way crashes. The data allowed estimating such probability via the indicator variable "crash," which equaled 1 if a data point represented an instance of wrong-way crash and equaled 0 if a data point represented a site with no recorded wrong-way crash (i.e., control corridors). Therefore, for a given set of conditions (e.g., traffic volume, median width), the average of the variable "crash" represented an estimate of the probability of a wrong-way crash. A logistic regression approach allowed researchers to model the relationships with potential explanatory variables as changes in the odds of a wrong-way crash occurring. The following relation defines the regression model:

$$Logit(\pi_{WW}) = \beta_0 + X \cdot \beta$$

Where

π_{WW} = Proportion of wrong-way crashes,
$Logit(\cdot)$ = Log-odds function, defined as $Logit(v) = log(v/1 - v)$,
X = Row vector of explanatory variables,
β = Vector of coefficients to be estimated, and
β_0 = Intercept term (to be estimated).

The impact of a change in one explanatory variable, X_1, is interpreted as a factor applied to the odds of wrong-way crashes before the change in X_1. This factor is known as the odds ratio and represents a multiplicative change in the odds of wrong-way crashes associated with a change in variable X_1. An odds ratio of 1.0 indicates no change in the odds of wrong-way crashes, while values smaller than 1.0 indicate a reduction in the odds of wrong-way crashes (e.g., 0.3 times as large). Similarly, values larger than 1.0 indicate an increase in the odds of wrong-way crashes (e.g., 1.2 times as large). When discussing odds ratios, it is common to express them in terms of "x times as big" independent of whether the impact is a decrease or increase. While the odds ratios could be equivalently expressed as a present decrease or increase, percentages are typically reserved for proportions and probabilities.

Modeling Process

Early in the modeling process, an examination of the range of key variables suggested that the dataset be further reduced for statistical analysis. First, the research team acknowledged

that crashes attributed to wrong-way maneuvers at ramps, median openings only (no intersecting roadway), and crossing the median were relatively small (8 percent, 7 percent, and less than 1 percent, respectively). The research team thought that these unique situations should not be evaluated in conjunction with the other types of wrong-way entries from intersecting roadways. Therefore, the research team removed these crashes from the dataset.

The research team also recognized that intersections with and without median openings are signed differently and thus should be analyzed separately. However, the dataset for intersecting roadways without a median opening included only 80 sites (11 percent), which did not provide an adequate sample size for further analysis. Thus, the focus of the statistical analysis was for sites with intersecting roadways with median openings. In addition, researchers included only sites with two through lanes in each direction (four through lanes total) because 90 percent of the sites had this main lane configuration.

Of the remaining sites, only 17 had medians wider than 120 ft, and most of these sites had STOP signs in the median opening. In contrast, for median widths 120 ft or less, all three types of control in the median opening were represented (i.e., no control, STOP sign, and YIELD sign). Researchers reviewed the impact of removing median widths larger than 120 ft on the modeling process and found no undue influence in the model parameter estimates. Therefore, researchers restricted the range for statistical analysis to sites with median widths less than or equal to 120 ft.

The modeling effort had various stages. Originally, a two-tier stepwise model selection scheme was implemented. First, for major design or operation variables (e.g., annual average daily traffic [AADT], median width, presence of turning lanes) and then at convergence, a new stepwise model selection procedure was started for traffic control device-type variables (i.e., signing and pavement markings).

Given the small sample size, it was expected that the models would have limited statistical power to pick up variables with relatively small effects, a feature that would limit potential findings about variables in the second stage of model selection. For this reason, the research team decided to develop linear combinations of signage variables through principal component analysis (PCA). As mentioned earlier, an additional round of model selection was performed using these combined variables where improved fits were obtained.

The final stage of modeling consisted of testing all models for some variable interactions and a careful examination and potential substitution of some variables for their collinear competitors that may have a more straightforward interpretation. Three criteria were computed to assess each model fit: cumulative residual plots, Hosmer-Lemeshow goodness-of-fit test, and receiver operating characteristic curves. All the final models scored acceptable to exceptional in all these metrics.

Traffic Control Device Variables Considered in the Analysis

A significant challenge associated with this analysis was the number of traffic control device variables collected for each site. Table 8 contains a list of the 29 traffic control device variables documented for each site. Figure 7 explains the sign location nomenclature used in Table 8.

Ideally, when the associations between these variables and odds of wrong-way crashes are of interest, a large enough sample size is required. However, the sample at hand was of a size that would only provide statistical evidence to detect associations between a reduced number of variables and the odds of wrong-way crashes. In addition, many of the traffic control device variables were strongly correlated. This was expected since many traffic control devices are installed and function as a system, not individual devices. This strong correlation tends to inflate the standard error of regression estimates; thus, increasing the sample size is necessary.

Given these characteristics, the research team anticipated that the modeling process would be able to identify a relatively small number of signage variables as key terms in the regression models. An exploration of the traffic control variables revealed that there was only one KEEP RIGHT sign in the dataset; thus, KEEP RIGHT signs were not included in the modeling process. In addition, researchers chose to focus on the signs on the near side of the median opening. Any significant finding could then be applied to the intersection of the minor approach with the opposing travel lanes. Researchers performed a PCA on the set of remaining traffic control device variables in order to identify combinations of these variables that would capture the most variability in the traffic control devices of the sites. The combinations of variables and their weights, as suggested by the resulting PCA, were then considered in a round of model selection.

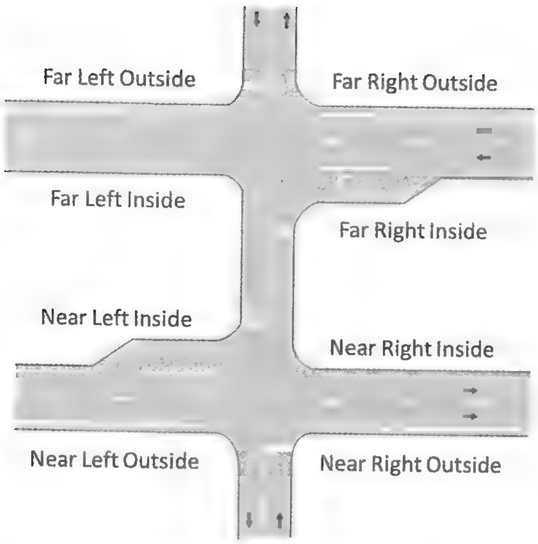
Results

The following sections contain the results of the modeling process for four different analyses of the final dataset (i.e., intersecting roadways with median openings, four through lanes, and median width less than or equal to 120 ft):

- High-speed rural divided highways—all wrong-way crashes,
- High-speed rural divided highways—nighttime wrong-way crashes,
- High-speed urban divided highways—all wrong-way crashes, and
- High-speed urban divided highways—nighttime wrong-way crashes.

Table 8. Traffic control device variables.

Expanded Variable Name	Short Variable Name	Variable Description
Type of Intersection Control	IntersectionTC_TTI	Type of control at intersection of minor and major roadways. 1 is none; 2 is STOP signs; 3 is YIELD signs; 4 is traffic signal.
Divided Highway Sign Near Right	NRDivided_Hwy_Sign	Presence of divided highway sign on the near right of the minor road approach. 1 for present; 0 for not present.
Divided Highway Sign Near Left	NLDivided_Hwy_Sign	Presence of divided highway sign on the near left of the minor road approach. 1 for present; 0 for not present.
Total Number of Divided Highway Signs	TotalNo_DH_Sign	Sum of divided highway signs.
ONE WAY Sign Near Right Outside	NROutOneWay_Sign	Presence of ONE WAY sign on the near right outside. 1 for present; 0 for not present.
ONE WAY Sign Near Left Inside	NLInsOneWay_Sign	Presence of ONE WAY sign on the near left inside. 1 for present; 0 for not present.
ONE WAY Sign Near Right Inside	NRInsOneWay_Sign	Presence of ONE WAY sign on the near right inside. 1 for present; 0 for not present.
ONE WAY Sign Far Right Inside	FRInOneWay_Sign	Presence of ONE WAY sign on the far right inside. 1 for present; 0 for not present.
ONE WAY Sign Far Left Outside	FLOutOneWay_Sign	Presence of ONE WAY sign on the far left outside. 1 for present; 0 for not present.
ONE WAY Sign Far Right Outside	FROutOneWay_Sign	Presence of ONE WAY sign on the far right outside. 1 for present; 0 for not present.
Total Number of ONE WAY Signs	TotalNo_OneWay_Sign	Sum of ONE WAY signs.
DO NOT ENTER Sign Near Left Outside	NLOutDNE_Sign	Presence of DO NOT ENTER sign on the near left outside. 1 for present; 0 for not present.
DO NOT ENTER Sign Near Left Inside	NLInsDNE_Sign	Presence of DO NOT ENTER sign on the near left inside. 1 for present; 0 for not present.
DO NOT ENTER Sign Far Right Inside	FRInsDNE_Sign	Presence of DO NOT ENTER sign on the far right inside. 1 for present; 0 for not present.
DO NOT ENTER Sign Far Right Outside	FROutDNE_Sign	Presence of DO NOT ENTER sign on the far right outside. 1 for present; 0 for not present.
Total Number of DO NOT ENTER Signs	TotalNo_DNE_Sign	Sum of DO NOT ENTER signs.
WRONG WAY Sign Near Left Outside	NLOutWW_Sign	Presence of WRONG WAY sign on the near left outside. 1 for present; 0 for not present.
WRONG WAY Sign Near Left Inside	NLInsWW_Sign	Presence of WRONG WAY sign on the near left inside. 1 for present; 0 for not present.
WRONG WAY Sign Far Right Inside	FRInsWW_Sign	Presence of WRONG WAY sign on the far right inside. 1 for present; 0 for not present.
WRONG WAY Sign Far Right Outside	FROutWW_Sign	Presence of WRONG WAY sign on the far right outside. 1 for present; 0 for not present.
Total Number of WRONG WAY Signs	TotalNo_WW_Sign	Sum of WRONG WAY signs.
Type of Interior Control	InteriorTC_TTI	Type of control in the median opening at wrong-way entry point. 1 is none; 2 is STOP signs; 3 is YIELD signs; 4 is traffic signal.
KEEP RIGHT Sign	KeepRight_Sign	Presence of KEEP RIGHT sign in the median opening. 1 for present; 0 for not present.
Stop or Yield Line in Median Opening	Stopbar_Crossover	Presence of stop or yield line in median opening. 1 for present; 0 for not present.
Stop or Yield Line on Minor Approach	Stopbar_MinorApproach	Presence of stop or yield line on minor approach. 1 for present; 0 for not present.
Centerline in Median Opening	Centerline_Crossover	Presence of centerline in median opening. 1 for present; 0 for not present.
Wrong-Way Arrow Markings Near Left	Near_WW Arrows	Present of wrong-way arrow markings on the near left side of the intersection. 1 for present; 0 for not present.
Wrong-Way Arrow Markings Far Right	Far_WW Arrows	Present of wrong-way arrow markings on the far right side of the intersection. 1 for present; 0 for not present.
Total Number of Traffic Control Devices in Field of View	TotalNo_TCD	Total number of traffic control devices present (sum of all signs and pavement markings).



Source: Texas A&M Transportation Institute.

Figure 7. Sign location nomenclature reference.

The probability of wrong-way crashes was used as the response variable in all the analyses. The datasets were made up of roughly a 50/50 split between sites with a history of wrong-way crashes and randomly selected control sites.

High-Speed Rural Divided Highways—All Wrong-Way Crashes

The overall high-speed rural divided highway dataset contained 297 sites. Table 9 contains the coefficients for the high-speed rural divided highway wrong-way crash model. This model shows that there was a multiplicative increase in the risk of wrong-way crashes associated with increasing traffic volume (i.e., AADT). It was estimated that each time the traffic volume doubles, the odds of wrong-way crashes increase by a factor of 1.91 ($\exp(2*0.934) = 1.910$). An increase in traffic volume means there are more vehicles on the roadway. Therefore, a driver making a wrong-way maneuver would be more likely to encounter another vehicle.

The presence of a centerline in the median opening was related with a reduction in the risk of wrong-way crashes. The odds of wrong-way crashes at locations with centerlines in the median opening were 0.316 times as large as the odds of wrong-way crashes at locations without this pavement marking ($\exp(-1.153) = 0.316$). Researchers believe the centerline in the median opening provides a visual cue for drivers that may draw their attention to the median opening and opposing traffic lanes.

Similarly, the presence of wrong-way arrow markings in the near main lanes near the intersection was found to be correlated with a reduction in wrong-way crash risk. The odds of wrong-way crashes at locations with wrong-way arrow markings were 0.258 times as large as the odds of wrong-way crashes at locations without this pavement marking ($\exp(-1.353) = 0.258$). Researchers believe that the wrong-way arrow markings indicate to drivers that both of the near main lanes are going in the same direction.

The presence of the DO NOT ENTER sign on the near left inside of the intersection was also found to be associated with a safety benefit. The odds of wrong-way crashes at locations with this sign were 0.351 times as large as the odds of wrong-way crashes at locations without this treatment ($\exp(-1.047) = 0.351$). The placement of the DO NOT ENTER sign in the median would provide a warning to drivers attempting to turn left into the near main lanes. As discussed previously, this maneuver was the cause of most of the wrong-way crashes in Texas and Iowa for which the wrong-way entry

Table 9. High-speed rural divided highway—wrong-way crash model.

Fixed Effects Coefficients	Estimate	Standard Error	z-value	p-value	Significance
log(AADT)	0.934	0.329	2.842	0.0045	**
Centerline in Median Opening	−1.153	0.545	−2.117	0.0342	*
Wrong-Way Arrows in Near Left Lanes	−1.353	0.616	−2.195	0.0282	*
Near Left Inside DO NOT ENTER Sign	−1.047	0.526	−1.990	0.0465	*
MUTCD Median Width (with Traffic Control in Median Opening)	0.015	0.013	1.203	0.2291	
MUTCD Median Width (without Traffic Control in Median Opening)	0.075	0.022	3.397	0.0007	***
Random Effects Coefficients					
Mean	−10.065	2.980	−3.378	0.0007	***
Standard Deviation	1.769				

* Statistically significant at the 5% significance level.
** Statistically significant at the 1% significance level.
*** Statistically significant at the 0.1% significance level.

point was known. Although not included in the modeling process, researchers believe this result would also be true for a DO NOT ENTER sign placed in the median on the far right side.

Finally, the correlation between wrong-way crashes and the median width was found to be dependent upon the presence of control in the median opening. At sites with a STOP or YIELD sign, there was no change in the risk of wrong-way crashes based on the median width (i.e., statistically equivalent to zero). Conversely, at sites without a STOP or YIELD signs, it was found that the odds of wrong-way crashes tended to increase by a multiplicative factor of 2.117 for every additional 10 ft of median width ($\exp(0.075*10) = 2.117$).

Figure 8 shows the type of control (i.e., none, STOP sign, or YIELD sign) in the median opening for the rural sites. MUTCD Figure 2B-16 does not show control in the median opening when the median width is less than 30 ft. In the rural dataset, this was the case for 11 percent of the sites. MUTCD Figure 2B-15 shows control (either a STOP or YIELD sign) in the median opening when the median width is greater than or equal to 30 ft. Most of the sites (55 percent) exhibited these characteristics. At 4 percent of the sites, a STOP or YIELD sign was located in the median opening even though the median width was less than 30 ft. However, 30 percent of the sites had a median width greater than or equal to 30 ft with no control in the median opening. The median widths in these instances were typically between 30 ft and 80 ft.

High-Speed Rural Divided Highways—Nighttime Wrong-Way Crashes

The nighttime high-speed rural divided highway dataset also contained 297 sites. However, in this model the indicator variable "crash" equaled 1 if a data point represented an instance of a nighttime wrong-way crash and 0 if a data point represented a site with no recorded nighttime wrong-way crash (i.e., control corridors and wrong-way crash corridors with only daytime wrong-way crashes).

Table 10 shows the coefficients for the high-speed rural divided highway nighttime crash model. As with the overall high-speed rural divided highway model, the presence of a centerline in the median opening and wrong-way arrow markings resulted in a reduction in the risk of nighttime wrong-way crashes ($\exp(-0.828) = 0.437$ and $\exp(-2.284) = 0.102$, respectively). The presence of the DO NOT ENTER sign on the near left inside of the intersection also made it into the model, but the significance of the correlation with nighttime wrong-way crashes was less (only statistically significant at a 10 percent level compared to 5 percent for the overall model).

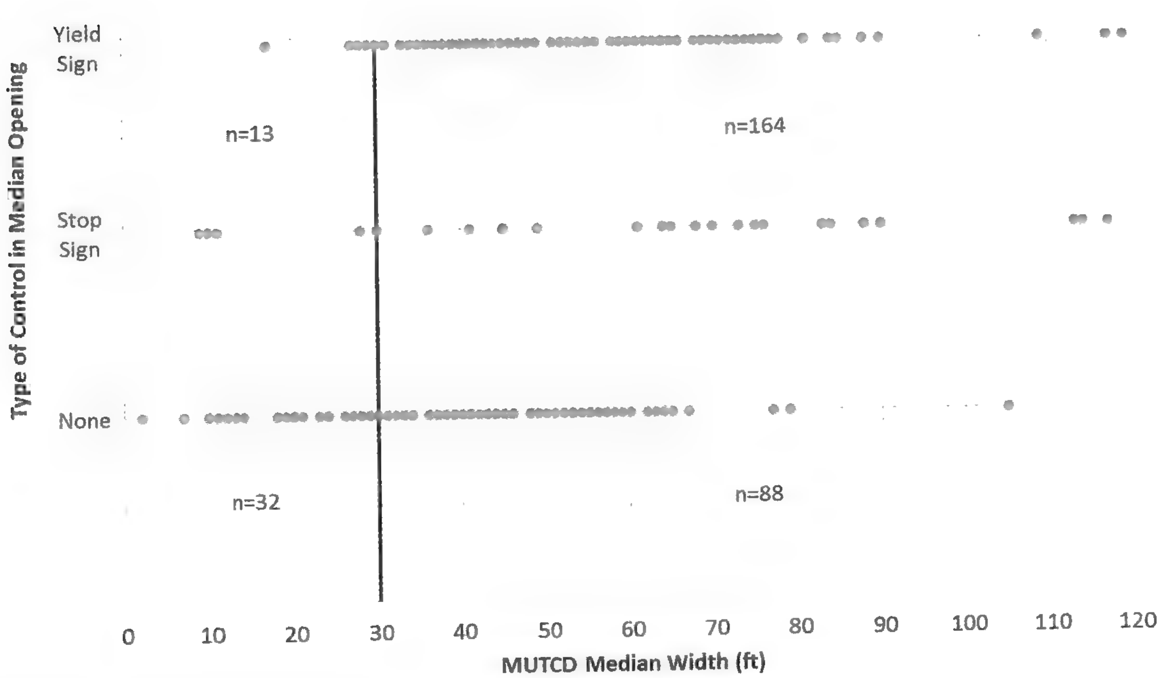


Figure 8. Type of control in the median opening—rural sites.

Table 10. High-speed rural divided highway—nighttime crash model.

Fixed Effects Coefficients	Estimate	Standard Error	z-value	p-value	Significance
Near Right Outside ONE WAY Sign[a]	−0.719	0.298	−2.414	0.0158	*
Near Left Inside ONE WAY Sign[a]	−0.719	0.298	−2.416	0.0157	*
Wrong-Way Arrows in Near Left Lanes	−2.284	0.812	−2.815	0.0049	**
Near Left Inside DO NOT ENTER Sign	−1.041	0.585	−1.780	0.0751	~
Stop or Yield Line in Median Opening[b]	−0.828	0.364	−2.277	0.0228	*
Centerline in Median Opening[b]	−0.828	0.364	−2.275	0.0229	*
Median Opening Width	0.012	0.006	1.823	0.0682	~
MUTCD Median Width (with Traffic Control in Median Opening)	0.030	0.016	1.918	0.0551	~
MUTCD Median Width (without Traffic Control in Median Opening)	0.083	0.026	3.176	0.0015	**
Random Effects Coefficients					
Mean	−3.555	0.386	−9.199	0.0000	***
Standard Deviation	1.861				

[a] Jointly estimated as an unweighted linear combination suggested by PCA.
[b] Jointly estimated as an unweighted linear combination suggested by PCA.
~ Statistically significant at the 10% significance level.
* Statistically significant at the 5% significance level.
** Statistically significant at the 1% significance level.
*** Statistically significant at the 0.1% significance level.

The presence of either the near right outside ONE WAY sign or near left inside ONE WAY sign was associated with a reduction in the risk of nighttime wrong-way crashes. The odds of nighttime wrong-way crashes reduced by a factor of 0.487 at locations with either of these signs compared to locations without these signs (exp(−0.719) = 0.487). Both of these ONE WAY signs are currently required in the MUTCD. The optional ONE WAY sign on the near right inside did not make it into the model. Only the ONE WAY signs on the near side were included in the modeling process. Even so, researchers believe this result would also be true for ONE WAY signs placed in the median on the far right inside or far left outside (i.e., where the median opening intersects with the opposing travel direction).

The presence of either a stop or yield line in the median opening was also associated with a reduction in the risk of nighttime wrong-way crashes. The odds of nighttime wrong-way crashes at locations with a stop or yield line in the median opening were 0.437 times as large as the odds of nighttime wrong-way crashes at locations without this treatment (0.437 = exp(−0.828)). Researchers believe that stop and yield lines in the median opening may provide yet another visual cue for drivers indicating that they should cross the near main lanes to reach the opposing travel lanes.

Similar to the findings for all wrong-way crashes at rural sites, the median width was found to be dependent upon the presence of control in the median opening. At sites with STOP or YIELD signs, researchers found a weak correlation (only statistically significant at a 10 percent level) between median width and nighttime wrong-way crashes. The odds of nighttime wrong-way crashes tended to increase by a multiplicative factor of 1.350 for every additional 10 ft of median width (exp(0.030*10) = 1.350). In comparison, at sites without a STOP or YIELD sign, researchers found that the odds of nighttime wrong-way crashes tended to increase by a multiplicative factor of 2.293 for every additional 10 ft of median width (exp(0.083*10) = 2.293) (statistically significant at a 1 percent level).

Researchers kept the median opening width in the final model because its presence improved the overall fit of the model. However, the correlation between the median opening width and nighttime wrong-way crashes was weak compared to the other variables (exp(0.012) = 1.012 and only statistically significant at a 10 percent level).

High-Speed Urban Divided Highways—Wrong-Way Crashes

The overall high-speed urban divided highway dataset contained 210 sites. Table 11 contains the coefficients for the high-speed urban divided highway wrong-way crash model. This is the only model in which a difference among the states was found. There was an increase in the risk of wrong-way crashes associated with urban sites located in California.

Table 11. High-speed urban divided highway—wrong-way crash model.

Fixed Effects Coefficients	Estimate	Standard Error	z-value	p-value	Significance
State of California	2.675	1.004	2.665	0.0077	**
Stop or Yield Line on Minor Approach[a]	–0.776	0.461	–1.683	0.0923	~
Near Left Divided Highway Sign[a]	–1.553	0.922	–1.683	0.0923	~
MUTCD Median Width (with Traffic Control in Median Opening)	–0.029	0.019	–1.550	0.1212	
MUTCD Median Width (without Traffic Control in Median Opening)	0.100	0.030	3.363	0.0008	***
Random Effects Coefficients					
Mean	–1.245	0.457	–2.722	0.0065	**
Standard Deviation	1.828				

[a] Jointly estimated as a weighted linear combination suggested by PCA.
~ Statistically significant at the 10% significance level.
** Statistically significant at the 1% significance level.
*** Statistically significant at the 0.1% significance level.

Given the small set of model covariates and the small sample of urban sites from California (n = 19), researchers speculate that there was a confounding, unaccounted factor that produced the increased risk.

Similar to the findings for the overall rural model, the median width was found to be dependent upon the presence of control in the median opening. At sites with a STOP or YIELD sign, there was no change in the risk of wrong-way crashes based on the median width (i.e., statistically equivalent to zero). Conversely, at sites without a STOP or YIELD sign, it was found that the odds of wrong-way crashes tended to increase by a multiplicative factor of 2.721 for every additional 10 ft of median width (exp(0.1001*10) = 2.721).

Figure 9 shows the type of control (i.e., none, STOP sign, or YIELD sign) in the median opening for the urban sites. Thirty-five percent of the sites had a median width less than 30 ft and no control in the median opening. In addition, 37 percent of the sites had a median width greater than or equal to 30 ft with either a STOP or YIELD sign in the median opening. At 8 percent of the sites, a STOP or YIELD sign was located in the median opening even though the median width was less than 30 ft. However, 20 percent of the sites had a median width greater than or equal to 30 ft with no control in the median opening. The median widths in these instances were typically between 30 ft and 50 ft.

The presence of a stop or yield line on the minor approach to the intersection and the presence of the near left divided highway sign were both loosely associated with a reduction in the risk of wrong-way crashes (statistically significant at only a 10 percent level). However, their inclusion improved the overall fit of the model. It should also be noted that the near left divided highway sign (which is optional in the MUTCD) was used at only nine sites and was always paired with a divided highway sign on the near right (which is required in the MUTCD for median widths greater than or equal to 30 ft). The near right divided highway sign did not make it into the model.

High-Speed Urban Divided Highways—Nighttime Wrong-Way Crashes

The overall high-speed urban divided highway dataset also contained 210 sites. As with the rural nighttime model, in the urban nighttime model, the indicator variable "crash" equaled 1 if a data point represented an instance of a nighttime wrong-way crash and 0 if a data point represented a site with no recorded nighttime wrong-way crash (i.e., control corridors and wrong-way crash corridors with only daytime wrong-way crashes). Table 12 shows the coefficients for the high-speed urban divided highway nighttime crash model.

The presence of a near left inside WRONG WAY sign was associated with a reduction in the risk of nighttime crashes. This sign was located on the same side of the road as the DO NOT ENTER sign that made it into the overall rural model and rural nighttime model (although its impact was less significant in the rural nighttime model). Again, signs placed in the median versus the outside of the roadway provide a warning to drivers attempting to turn left into the near main lanes. The odds of nighttime wrong-way crashes at locations with a near left inside WRONG WAY sign were 0.495 times as large as the odds of nighttime wrong-way crashes at locations without this treatment (exp(–0.704) = 0.495).

The presence of the near left divided highway sign (which is optional in the MUTCD) was associated with a more significant reduction in the risk of nighttime wrong-way crashes (statistically significant at a 5 percent level). However, the small sample size (n = 9) limits the practicality of this finding.

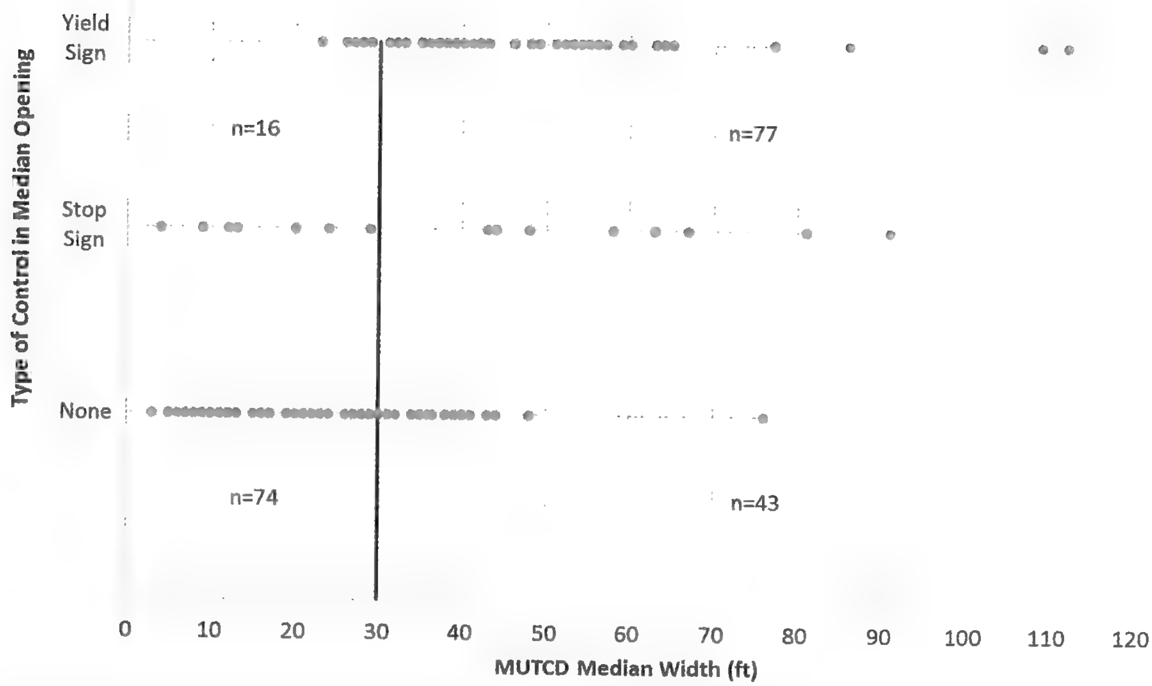


Figure 9. Type of control in the median opening—urban sites.

Table 12. High-speed urban divided highway—nighttime crash model.

Fixed Effects Coefficients	Estimate	Standard Error	z-value	p-value	Significance
Near Left Inside WRONG WAY Sign[a]	–0.704	0.352	–1.999	0.0456	*
Near Left Divided Highway Sign[a]	–2.111	1.056	–1.999	0.0456	*
Stop or Yield Line on Minor Approach[a]	–0.704	0.352	–1.999	0.0456	*
MUTCD Median Width (with Traffic Control in Median Opening)	–0.022	0.014	–1.624	0.1045	
MUTCD Median Width (without Traffic Control in Median Opening)	0.049	0.019	2.594	0.0095	**
Median Opening Width	–0.011	0.006	–1.812	0.0700	~
Near Left-Turn Lane	–0.715	0.396	–1.805	0.0711	~
Random Effects Coefficients					
Mean	–1.190	0.006	–198.297	0.0000	***
Standard Deviation	0.7304				

[a] Jointly estimated as a weighted linear combination suggested by PCA.
~ Statistically significant at the 10% significance level.
* Statistically significant at the 5% significance level.
** Statistically significant at the 1% significance level.
*** Statistically significant at the 0.1% significance level.

The presence of a stop or yield line on the minor approach was also associated with a more significant reduction in the risk of nighttime wrong-way crashes. The odds of nighttime wrong-way crashes at locations with a stop or yield line on the minor approach were 0.495 times as large as the odds of nighttime wrong-way crashes at locations without this pavement marking (exp(−0.704) = 0.460).

Similar to the findings for the other three models, the median width was found to be dependent upon the presence of control in the median opening. At sites with a STOP or YIELD sign, there was no change in the risk of wrong-way crashes based on the median width (i.e., statistically equivalent to zero). In contrast, at sites without a STOP or YIELD sign, it was found that the odds of nighttime wrong-way crashes tended to increase by a multiplicative factor of 1.632 for every additional 10 ft of median width (exp(0.049*10) = 1.632).

Researchers kept the median opening width and the presence of the near left-turn lane in the final model because these variables improved the overall fit of the model. However, the correlation between these two variables and nighttime wrong-way crashes was weak compared to the other variables (statistically significant at only a 10 percent level).

Median Width Threshold for Control in the Median Opening

Because the effects of median widths at sites without control in the median opening were found to monotonically increase (i.e., without peaking), the research team decided to use the high-speed rural divided highway crash model that included all wrong-way crashes to investigate if a minimal threshold for recommending the use of median opening control (i.e., STOP or YIELD sign) could be determined. Researchers selected the rural model instead of the urban model because of the wider range of median widths without control in the median opening in the rural dataset.

Researchers compared the magnitude of the effect of median width to the amount of unexplained variability of differences between sites, after accounting for the effects of other variables. The rationale was that although this analysis found an increasing effect for increasing median widths, such an effect may not be practically significant when considering the random variability in the odds of wrong-way crashes from site to site. If the variability was large compared to the change in odds linked to median width, such an expected change should be virtually undetectable. However, it was also anticipated that for a wide enough median, the expected increase in odds of wrong-way crashes associated with median width should be clearly observable, even when the random variation in the odds of wrong-way crashes due to differences between sites was present.

Figure 10 shows the log-odds line of the effect of median width (compared to median width equal to 0 ft) and the 90 percent and 95 percent confidence envelope of uncertainty associated with variability between sites (i.e., the model random effect variance). It can be seen that, depending on the

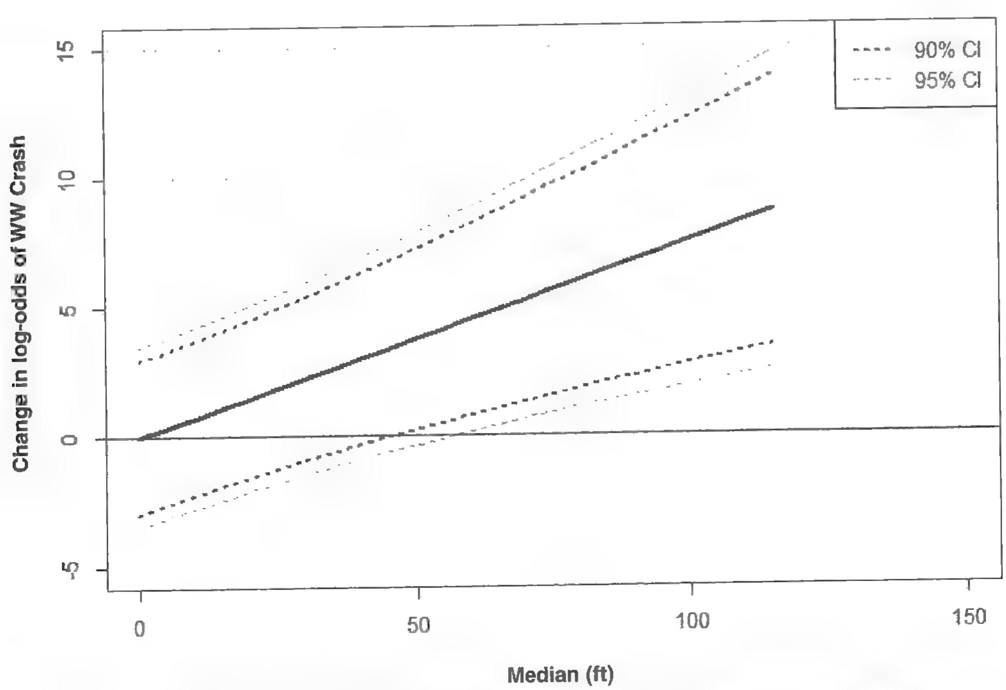


Figure 10. Log-odds median width effect plus random effect (without control in the median opening).

level of confidence desired, the increase in wrong-way crash log-odds associated with median width should be clearly identifiable for median widths of about 50 ft or wider.

Summary

This chapter documented the exploratory and statistical analyses of wrong-way crashes on high-speed divided highways. Researchers found that most of the wrong-way crashes on these roadways resulted in serious injury, occurred over the weekend (Friday through Sunday), and happened at night. More than two-thirds of the wrong-way crashes resulted from a wrong-way maneuver from an intersecting roadway where a median opening was present. Overall, females comprised about one-third of the wrong-way drivers, while males represented two-thirds of the wrong-way drivers. Older drivers (≥ 60) and those ages 21 to 29 comprised more than 60 percent of the wrong-way drivers.

The safety analysis found that there were numerous sites where the traffic control in the median opening did not fully comply with the MUTCD with respect to treating the location as one or two intersections. Primarily this was represented in narrow medians (less than 30 ft) with a STOP or YIELD sign in the median opening (6 percent) or in wide medians (greater than or equal to 30 ft) with no STOP or YIELD sign in the median opening (26 percent). This may be an indication that practitioners are using engineering judgment to determine the most effective installation of interior right-of-way devices to address safety and operations at divided highway junctions. *NCHRP Report 375: Median Intersection Design* (Harwood et al. 1995) found a similar deviation in the interior right-of-way traffic control treatments for median widths between 30 ft and 85 ft (median width included left-turn lanes, if present). There was also evidence from the safety analysis that the criterion may be 50 ft instead of 30 ft. Additional specific findings from the safety analysis include the following:

- Greater use of ONE WAY signs (above those that are required) does not appear to deter wrong-way movements.
- There was limited evidence that use of the required divided highway sign on the crossroad exterior approaches deters wrong-way movement.
- The placement of DO NOT ENTER and WRONG WAY signs on the inside turn of a wrong-way movement (side of divided highway nearer the right-of-way line) does not deter wrong-way movements.
- Treatments that appear to deter wrong-way movements include:
  - DO NOT ENTER and WRONG WAY signs on the outside of a wrong-way turn,
  - Wrong-way arrow markings for the through lanes on the divided highway,
  - Presence of a centerline in the median opening, and
  - Use of stop or yield lines when interior right-of-way treatments are provided.

CHAPTER 3

Active Countermeasures for Freeways

Since the 1960s, transportation agencies have been implementing and testing active detection and warning systems to deter wrong-way entries onto freeways (e.g., Tamburri and Theobald 1965; Tamburri 1965; Rinde 1978; Knight 1983; Moler 2002; Cooner et al. 2004; American Traffic Safety Services Association 2014). More recently, agencies have been installing systems that activate flashing LEDs within the borders of WRONG WAY and DO NOT ENTER signs and are experimenting with red RFBs in conjunction with WRONG WAY signs to increase the sign's conspicuity. This chapter provides a brief overview of applications of these two countermeasures in Texas and Florida, and documents the research methodology, analysis, and results of evaluations conducted.

LEDs within the Border of WRONG WAY Signs

For the evaluation of the effectiveness of LED border-illuminated WRONG WAY signs, the research team analyzed wrong-way driving (WWD) event datasets from San Antonio, Texas, as well as South Florida. The sections below provide a brief history of the LED border-illuminated WRONG WAY sign implementations in each state, document the findings of the analysis in each state, and provide some additional statistics gleaned from both datasets.

Texas

Background

At approximately 2:00 a.m. on March 15, 2011, a head-on collision occurred in San Antonio, Texas. This crash was caused by a driver who had entered the interstate going in the wrong direction. Both the wrong-way driver and right-way driver (a San Antonio Police Department [SAPD] patrol officer) were killed. Although there had been multiple wrong-way driver events in San Antonio previous to this crash, the death of the SAPD officer resulted in a significant response from law enforcement, the media, and the public.

In May 2011, public transportation and law enforcement agencies in the San Antonio area created a WWD task force to share information and identify means to address and reduce WWD activity. The task force used various methods to document WWD activity in San Antonio, with the purpose of identifying where WWD countermeasure deployment would be most meaningful and effective. After analyzing the various WWD event data sources and information details available from each source, analysts determined that insufficient information existed to link WWD events with specific freeway ramps where wrong-way drivers entered the freeway network. Accordingly, there was no logical means that could be devised for prioritizing the treatment of one freeway ramp over another. Thus, the task force concluded that treatment of an entire freeway corridor was necessary in order to determine the effectiveness of WWD countermeasures.

The task force selected the 15-mi US 281 corridor from I-35 (near downtown) to just north of Loop 1604 (the far north central side of San Antonio) as the Wrong-Way Driver Countermeasure Operational Test Corridor. Between March 2012 and June 2012, Texas DOT staff and contractors installed WRONG WAY signs with flashing red LEDs around the border at 26 exit ramps in the US 281 test corridor (see Figure 11 and Figure 12). The purpose of the flashing red LEDs was to increase the conspicuity of WRONG WAY signing at night. Originally, a single radar unit was installed to detect wrong-way vehicles and activate the flashing red LEDs. However, sustained false alarm issues with the single radar setup led to deactivation of detection components. Therefore, the signs were set to flash under low ambient light conditions (i.e., at night and during some inclement weather events), whether or not a wrong-way vehicle was detected. Texas DOT thought that this operation was acceptable because it could potentially catch the attention of a wrong-way driver approaching on the frontage road, instead of waiting until the wrong-way vehicle

Source: Texas A&M Transportation Institute.

Figure 11. WRONG WAY sign with flashing red LEDs around border.

was driving up the ramp. More recent implementations of these systems in Fort Worth activate the flashing LEDs only when a wrong-way vehicle is detected. The more recent systems include multiple radars and a camera to reduce false alarms and provide visual confirmation of the wrong-way vehicle, respectively.

Where the length and design of the exit ramp allowed, WRONG WAY signs with flashing red LEDs around the border supplemented the existing static WRONG WAY signs. On shorter ramps, the WRONG WAY signs with flashing red LEDs around the border replaced the existing static WRONG WAY signing. The battery for the signs was encased in the sign pole and charged by a small solar array attached to the top of the sign support.

Data Sources

Even before the task force was created, SAPD and Texas DOT implemented several procedures with regard to responding to WWD events. In August 2010, SAPD began to use an emergency call signal (i.e., E-tone) for its radio network when a wrong-way driver was reported to 911. In January 2011, SAPD implemented a code in its computer-aided dispatch system that specifically identified all wrong-way driver events. Similarly, in March 2011, Texas DOT TransGuide traffic management center (TMC) operators began logging all WWD events, not just those that resulted in a crash.

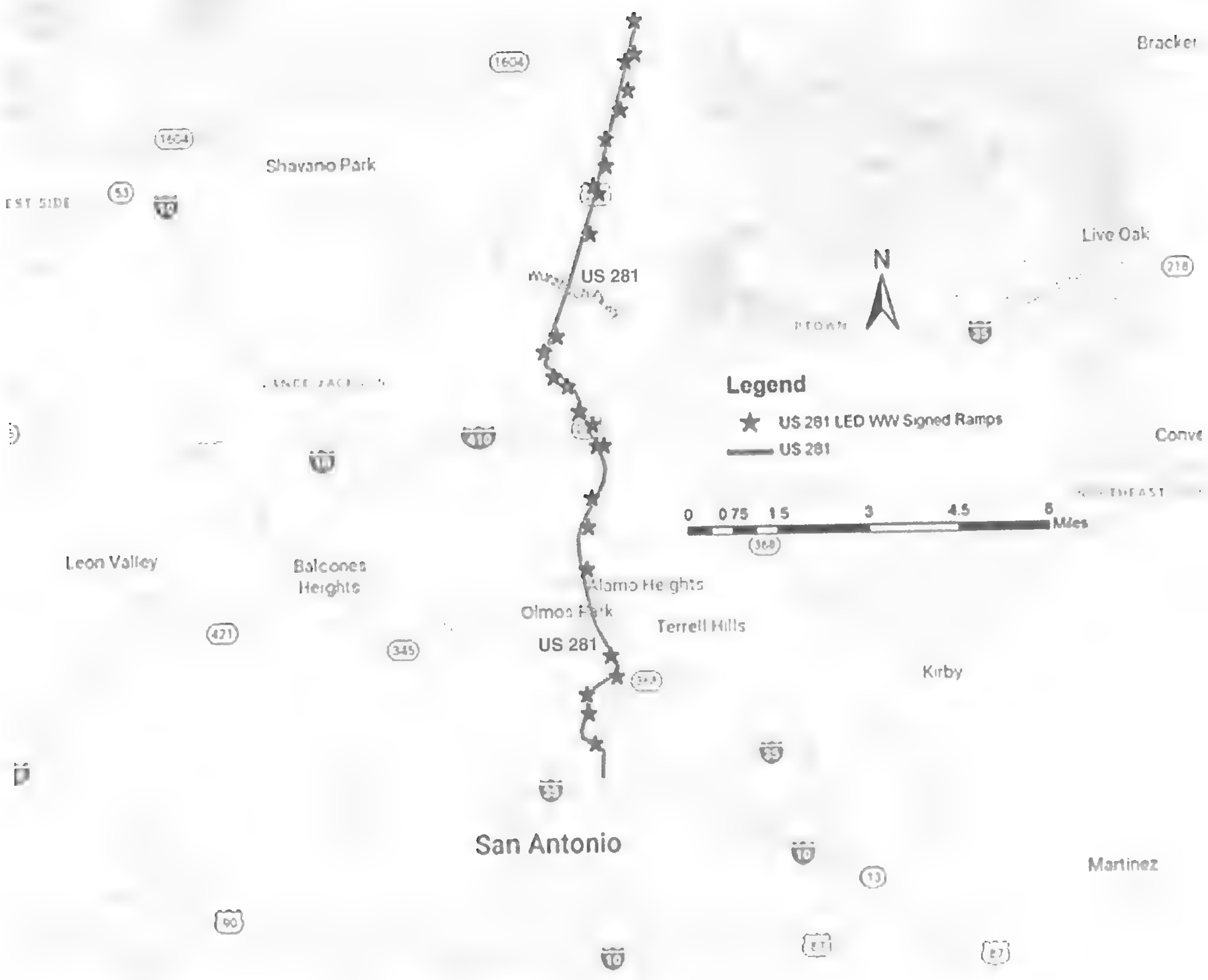
Through their involvement in the San Antonio WWD task force, both SAPD and Texas DOT shared the WWD subcomponent of their data logs for the border-illuminated WRONG WAY signing evaluation. However, the Texas DOT TransGuide operator logs generally included only the events that occurred in its coverage area—about half of the freeways in the San Antonio region.

Researchers also extracted WWD-involved crash information from the Texas DOT CRIS. However, because CRIS only documents WWD-related crashes, rather than any event where WWD activity is observed, the number of records was small compared to the SAPD 911 WWD call logs and the Texas DOT TransGuide operator WWD logs. Overall, researchers primarily used the SAPD 911 call logs for the statistical analysis because these logs began in January 2011, continued without interruption through April 2016, and contained more data points.

Results

Researchers performed a before-after evaluation with a control group to determine whether or not a meaningful reduction in WWD events was observed along the US 281 test corridor (Gross et al. 2010). The control data were all of the WWD events in the remainder of the city of San Antonio (but not including the US 281 test corridor). The before period was 14 months long (January 2011 to February 2012). Researchers could not test the comparability of the treatment and control datasets before the LED border-illuminated WRONG WAY signs were installed because only one complete year of WWD event data were available (i.e., SAPD began coding all wrong-way driver events in January 2011). The WRONG WAY signs with flashing red LEDs around the border were installed between March 2012 and June 2012. Researchers did not include data from this time period in the analysis because the traffic control devices in the corridor were in flux. The after period was 46 months long (July 2012 to April 2016).

Table 13 shows the before and after WWD event data for the treatment and control groups in San Antonio. From these data, researchers computed an event modification factor (EMF) of 0.68 with a 95 percent confidence interval of 0.45 to 0.91. Because the confidence interval does not include 1.0, it can be stated with 95 percent confidence that the treatment had an effect. In terms of the expected change in events, the EMF indicates a 32 percent reduction in the WWD events on the US 281 test corridor after the installation of WRONG WAY signs with flashing red LEDs around the border at all exit ramps in the corridor. In other words, the WWD events at the exit ramps with the border-illuminated WRONG WAY signs were reduced by about one-third. This percentage change was statistically significant at a 5 percent significance



Source: Texas A&M Transportation Institute and map data © 2017 Google.

Figure 12. US 281 LED border-illuminated WRONG WAY sign pilot test corridor.

level ($\alpha = 0.05$), and the 95 percent confidence interval was −55 percent to −9 percent.

In 2014, Finley et al. (2014) found similar results for WRONG WAY signs with flashing red LEDs around the border based on 14 months of before data and 22 months of after data. At that time, researchers calculated a 38 percent reduction in WWD events on the US 281 corridor after the installation of the signs. This percent change was statistically significant at a 5 percent significance level, and the 95 percent confidence interval was −63 percent to −13 percent. While the more recent percent reduction in WWD events is slightly less (32 percent), the expanded dataset findings show the long-term effectiveness of these signs.

Florida

Background

Florida's Turnpike Enterprise (FTE) has installed WWD countermeasures along part of its roadway network in South Florida. These countermeasures consist of border-illuminated WRONG WAY signs, radar, cameras, and communication abilities (see Figure 13). When the radar detects a wrong-way vehicle, the red LED lights flash before the vehicle reaches the sign. Once the vehicle reaches the sign, a series of photos is taken from a side camera and sent to FTE's TMC and Florida Highway Patrol's (FHP's) command center. FTE installed these technologies at six interchanges (12 ramps) on the

Table 13. San Antonio WWD event data and computations.

Time Period	Treatment Group (n = 96)	Control Group (n = 1073)
Before	46	396
After	135	1667

Primary computations:
EMF = (Observed$_{T,A}$/Expected$_{T,A}$)/(1+(VarianceExpected$_{T,A}$/Expected$_{T,A}$^2)) = 0.68
95 Percent Confidence Interval = EMF±1.96*EMF Standard Error = 0.45 to 0.91
Percent reduction = (1 – EMF)*100 = 32

Additional computations:
Comparison ratio = Observed$_{C,A}$/Observed$_{C,B}$ = 4.20
Expected$_{T,A}$ = Observed$_{T,B}$*comparison ratio = 193.64
VarianceExpected$_{T,A}$ = Expected$_{T,A}$^2*(1/Observed$_{T,B}$+1/Observed$_{C,B}$+1/Observed$_{C,A}$) = 932.34
VarianceEMF = (EMF^2*[(1/Observed$_{T,A}$)+(VarianceExpected$_{T,A}$/Expected$_{T,A}$^2)]/[1+(VarianceExpected$_{T,A}$/Expected$_{T,A}$^2)]^2 = 0.01
EMF Standard Error = SQRT(VarianceEMF) = 0.12

EMF = Event Modification Factor
Observed$_{T,A}$ = Observed Treatment After
Expected$_{T,A}$ = Expected Treatment After
VarianceExpected$_{T,A}$ = Variance of the Expected Treatment After
Observed$_{C,A}$ = Observed Control After
Observed$_{C,B}$ = Observed Control Before
Observed$_{T,B}$ = Observed Treatment Before
VarianceEMF = Variance of the EMF
SQRT = Square Root

Homestead Extension of Florida's Turnpike (HEFT SR 821) and five interchanges (five ramps) on the Sawgrass Expressway (SR 869). The HEFT also contains mainline detectors around the test interchanges. These 17 ramps are listed in Table 14 and depicted in Figure 14 and Figure 15. Note that northbound and southbound ramps are equipped on SR 821, while only southbound ramps are equipped on SR 869 (Al-Deek et al. 2016).

Source: University of Central Florida.

Figure 13. FTE border-illuminated WRONG WAY sign warning system.

Data Sources

The research team examined the number of crashes, police citations, 911 calls, and system alerts before and after the installation of the border-illuminated WRONG WAY sign warning system. The before and after periods were March 2013 to

Table 14. FTE border-illuminated WRONG WAY sign warning system pilot test locations.

Ramp Number	Ramp Location and Direction
1	821 NB OFF 29—NW 41
2	821 SB OFF 29—NW 41
3	821 NB OFF 31—NW 74 ST
4	821 SB OFF 31—NW 74 ST
5	821 NB OFF 34—NW 106
6	821 SB OFF 34—NW 106
7	821 NB OFF 35—US 27
8	821 SB OFF 35—US 27
9	821 NB OFF 43—NW 57
10	821 SB OFF 43—NW 57
11	821 NB OFF 47—NW 27
12	821 SB OFF 47—University
13	869 SB OFF 1—Sunrise
14	869 SB OFF 3—Oakland
15	869 SB OFF 5—Commerce
16	869 SB OFF 8—Atlantic
17	869 SB OFF 11—Sample

Source: University of Central Florida.

Figure 14. HEFT (SR 821) FTE pilot test interchanges.

Source: University of Central Florida.

Figure 15. Sawgrass Expressway (SR 869) FTE pilot test interchanges.

September 2014 (19 months) and November 2014 to May 2016 (19 months), respectively. FTE installed the systems in October 2014. The analysis used a set of control interchanges without the countermeasures on the FTE system for comparison with the pilot test interchanges. There was a total of 29 control interchanges located on SR 821, SR 869, and SR 91 in Miami-Dade and Broward Counties.

Table 15 contains a summary of the data sources for the before and after periods for the pilot test interchanges, a random sample of the control interchanges, and all of the control interchanges. The WWD events shown in this table are events that occurred in the vicinity of either the test or control interchanges. This does not mean that all WWD events originated at these interchanges but that these interchanges were nearest to the events and therefore the most likely points of origin. Table 15 shows that there was a small number of recorded crashes and citations during the study period. As with the Texas data, the research team focused on the WWD 911 calls that were reported to TMC for statistical analysis because the entire dataset contained all WWD events and many more data points.

Table 15. Summary of SunGuide WWD events for test and control sites.

Miami-Dade and Broward Counties	Before Period Crashes	After Period Crashes	Before Period Citations	After Period Citations	Before Period 911 Calls	After Period 911 Calls
Test Interchanges (n = 11)	1	1	3	5	16	24
Random Control Interchanges (n = 11)	1	2	0	4	15	22
Total Control Interchanges (n = 29)	4	5	10	14	37	51
Total (n = 40)	5	6	13	19	53	75

Results

To assess the effectiveness of the border-illuminated WRONG WAY signs in Florida, the research team performed a before-after evaluation with a control group to determine whether or not a meaningful reduction in WWD events was observed at the pilot test locations (Gross et al. 2010). The control group contained 11 similarly designed interchanges on the FTE system in South Florida near the test ramps (see Table 16). The research team conducted a test of comparability for the treatment group and potential control group to assess the suitability of the candidate control group (Hauer 1997). Table 17 shows the test of comparability dataset for 4 years and odds ratio computations. The mean of the individual odds ratios was 0.91, which is reasonably close to 1.0, and the standard deviation was 0.13. The 95 percent confidence interval was 0.66 to 1.16. Because the mean was close to 1.0 and the 95 percent confidence interval included 1.0, the research team concluded that the control group was suitable.

Table 18 shows the before and after WWD event data for the treatment and control groups in South Florida. From these data, researchers computed an EMF of 0.81 with a 95 percent confidence interval of 0.19 to 1.43. In terms of the expected change in events, the EMF indicates a 19 percent reduction in the WWD events at the treatment sites after the installation of WRONG WAY signs with flashing red LEDs around the border. However, because the confidence interval includes 1.0, it cannot be stated with 95 percent confidence that the treatment had an effect.

WWD Event Statistics

The research team also used the WWD event data on freeways in Texas and South Florida to examine some general characteristics of these incidents. In particular, the research team wanted to provide insight into the distance the wrong-way driver traveled and the time span of the WWD events. In order to determine these two items of interest, the research team needed to identify WWD events with more than one call to 911. Out of the 2428 WWD events that occurred in San Antonio, Texas, between January 1, 2011, and April 30, 2016, 607 were multi-call events. In South Florida between January 1, 2006, and April 30, 2016, there were 283 multi-call events out of 1485 WWD events.

Figure 16 shows the distance the wrong-way driver traveled for the multi-call WWD events, and Figure 17 shows the time span (i.e., duration) of each multi-call WWD event. Since

Table 16. Treatment and control group ramps.

Treatment Location	Treatment Interchange Geometry	Control Location	Control Interchange Geometry
Exit 29 on SR 821	Partial Cloverleaf	Exit 5 on SR 821	Partial Cloverleaf
Exit 31 on SR 821	Three-Leg Directional	Exit 16 on SR 821	Split Diamond
Exit 34 on SR 821	Three-Leg Directional	Exit 17 on SR 821	Two-Leg Directional
Exit 35 on SR 821	Partial Cloverleaf	Exit 20 on SR 821	Partial Cloverleaf
Exit 43 on SR 821	Partial Cloverleaf	Exit 23 on SR 821	Partial Cloverleaf
Exit 47 on SR 821	Partial Cloverleaf	Exit 25 on SR 821	Partial Cloverleaf
Exit 1 on SR 869	Full Diamond	Exit 39 on SR 821	Two-Leg Directional
Exit 3 on SR 869	Full Diamond	Exit 14 on SR 869	Full Diamond
Exit 5 on SR 869	Full Diamond	Exit 15 on SR 869	Full Diamond
Exit 8 on SR 869	Full Diamond	Exit 19 on SR 869	Full Diamond
Exit 11 on SR 869	Full Diamond	Exit 53 on SR 91	Full Diamond

Table 17. WWD events before treatment was installed.

Group	Year 1 (October 2010–September 2011)	Year 2 (October 2011–September 2012)	Year 3 (October 2012–September 2013)	Year 4 (October 2013–September 2014)
Treatment	11	12	8	11
Control	8	9	6	11

Primary computations:
Years 1 & 2 Odds Ratio = $((Treatment_B*Control_A)/(Treatment_A*Control_B))/(1+ (1/Treatment_A)+(1/Control_B))$ = 0.85
Years 2 & 3 Odds Ratio = 0.81
Years 3 & 4 Odds Ratio = 1.06
Mean Odds Ratio = 0.91
Standard Deviation = 0.13
95 Percent Confidence Interval = Mean Odds Ratio±1.96*Standard Deviation = 0.66 to 1.16

$Treatment_B$ = Total WWD events for the treatment group in year i
$Treatment_A$ = Total WWD events for treatment group in year j
$Control_B$ = Total WWD events for control group in year i
$Control_A$ = Total WWD events for control group in year j

these distances and times are based on calls to 911, the actual distance traveled by the wrong-way driver and the duration of the event could be longer. However, the research team believes these data provide critical insight into the characteristics of WWD events. Figure 16 does not include the multi-call WWD events where the reported location of each call was the same (25 percent and 65 percent for Texas and South Florida, respectively). Figure 17 does not include the multi-call WWD events where the reported time of each call was the same (11 percent and 63 percent for Texas and South Florida, respectively).

According to Figure 16, the distance the wrong-way driver traveled for the multi-call WWD events was similar between the two datasets. The only exceptions appear to be that there were fewer wrong-way drivers that traveled 1 mi or less and more wrong-way drivers that traveled 15 mi or more in South Florida. Overall, approximately two-thirds of the wrong-way drivers traveled 3 mi or less. However, this figure does show

Table 18. FTE WWD event data and computations.

Time Period	Treatment Group (n = 43)	Control Group (n = 37)
Before	18	15
After	25	22

Primary computations:
EMF = $(Observed_{T,A}/Expected_{T,A})/(1+(VarianceExpected_{T,A}/Expected_{T,A}\string^2))$ = 0.81
95 Percent Confidence Interval = EMF±1.96*EMF Standard Error = 0.19 to 1.43
Percent reduction = (1 – EMF)*100 = 19

Additional computations:
Comparison ratio = $Observed_{C,A}/Observed_{C,B}$ = 1.47
$Expected_{T,A} = Observed_{T,B}$*comparison ratio = 26.4
$VarianceExpected_{T,A} = Expected_{T,A}\string^2*(1/Observed_{T,B}+1/Observed_{C,B}+1/Observed_{C,A})$ = 116.86
VarianceEMF = $(EMF\string^2*[(1/Observed_{T,A})+(VarianceExpected_{T,A}/Expected_{T,A}\string^2)]/[1+(VarianceExpected_{T,A}/Expected_{T,A}\string^2)]\string^2$ = 0.10
EMF Standard Error = SQRT(VarianceEMF) = 0.32

EMF = Event Modification Factor
$Observed_{T,A}$ = Observed Treatment After
$Expected_{T,A}$ = Expected Treatment After
$VarianceExpected_{T,A}$ = Variance of the Expected Treatment After
$Observed_{C,A}$ = Observed control after
$Observed_{C,B}$ = Observed control before
$Observed_{T,B}$ = Observed treatment before
VarianceEMF = Variance of the EMF
SQRT = Square Root

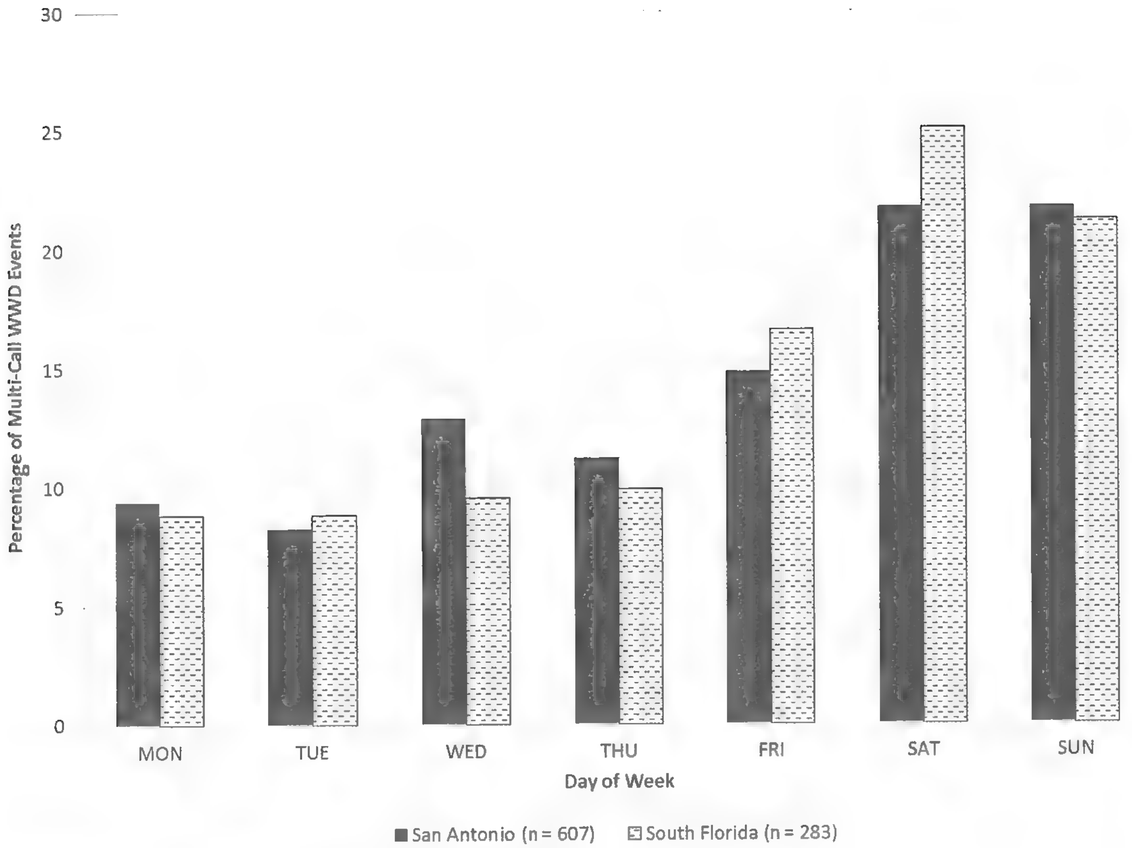


Figure 19. 911 multi-call events by day of week.

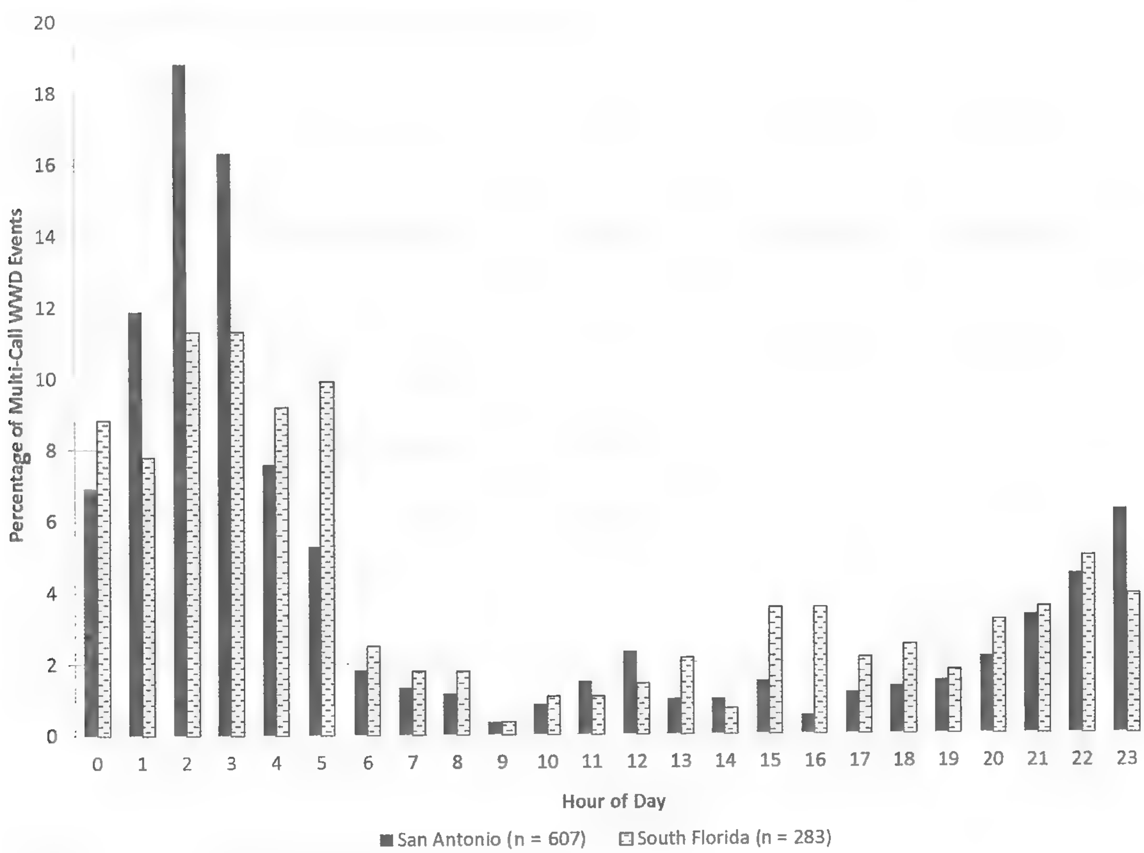


Figure 20. 911 multi-call events by hour of day.

Background

The first WWD study, conducted by the University of Central Florida for CFX in 2013, showed that there was a need to detect and deter WWD on CFX's roadways (Al-Deek et al. 2013). To achieve this objective, University of Central Florida researchers suggested a variety of WWD countermeasures with a hierarchy of technology and differing levels of intervention. One of these countermeasures was the concept of using WRONG WAY signs equipped with red rectangular rapid flashing beacons (RRFBs). Based on this suggestion, CFX submitted a request to experiment with red RRFBs as a WWD countermeasure to FHWA. This request to experiment was approved by FHWA in October 2014.

While early documentation of the system referred to the devices as red RRFBs, further investigation into the actual red flashing pattern revealed that it was different than the approved pedestrian RRFB indications (i.e., 800-millisecond flash cycle length with a 2–5 or wig-wag plus simultaneous flash [WW+S] pattern). The red flashing pattern cycle length is 20 seconds with the following wig-wag pattern (also see Table 19):

- The top left side and bottom right side beacons are on for 500 milliseconds.
- The top right side and bottom left side beacons are on for 500 milliseconds.

Thus, the duty cycle is 1 second and each beacon is on for 50 percent of its duty cycle. Because the red flashing pattern did not contain a rapid flash component, the research team refers to the WWD countermeasure as red RFBs in this report.

CFX chose to pilot test red RFBs at the following five ramps based on the results of the first WWD study (Al-Deek et al. 2013, 2015):

- SR 528 and SR 520—one off ramp (eastbound off ramp).
- SR 408 and Hiawassee Road—two off ramps.
- SR 408 and Kirkman Road—two off ramps.

Figure 21 shows the general location of the sites. Figure 22 shows the SR 528 eastbound off ramp pilot site, with the ramp highlighted in red. CFX and its contractors installed and tested the first sets of WRONG WAY signs with RFBs at this site. The implementation date for this site was February 21, 2015. Figure 23 shows the four test sites on SR 408, with the ramps highlighted in red. The implementation date for these four sites was June 14, 2015. Additionally, CFX decided to improve its WWD detection capabilities to more accurately determine the frequency of WWD on its roadways.

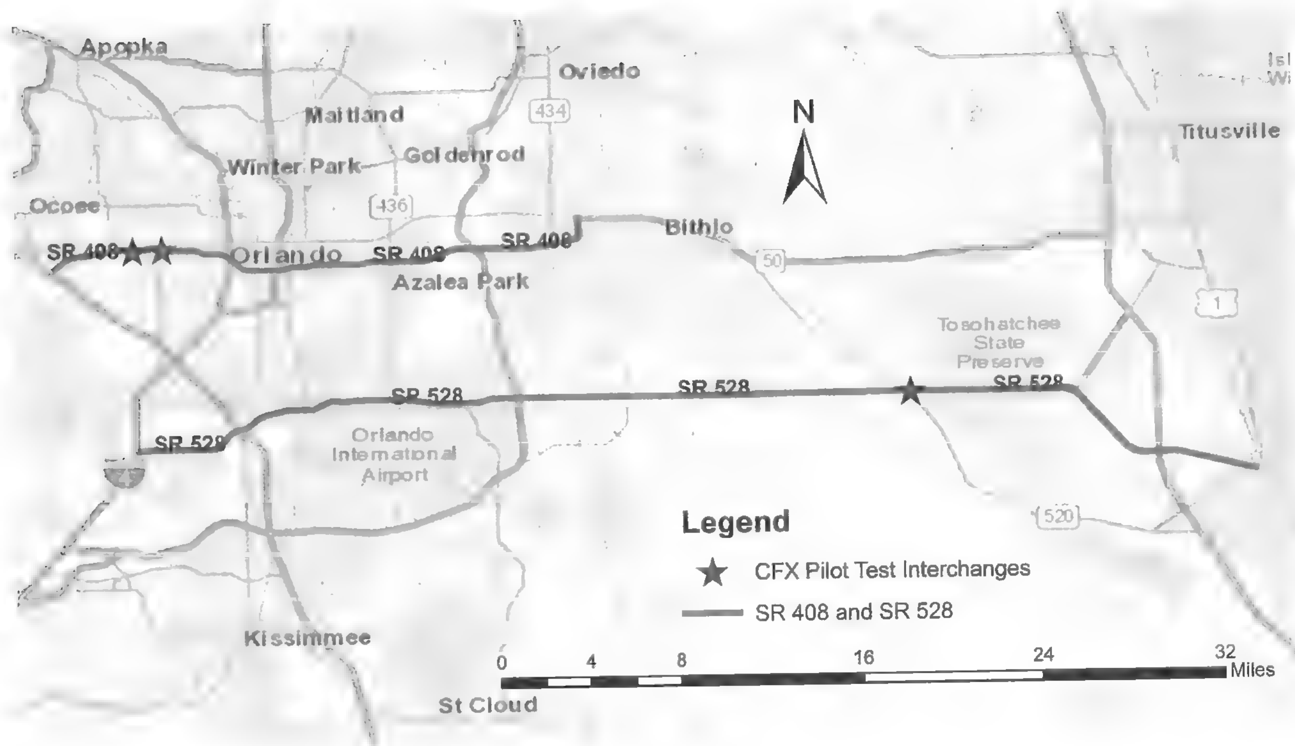
The RFB WRONG WAY sign setup consists of one pair of signs (one sign on each side of the road) near the ramp intersection with the frontage road (first set of signs) and one pair of signs closer to the mainline (second set of signs). Figure 24 shows the components of the RFB sign system. All four sign assemblies at each site have a WRONG WAY sign with one red RFB above the sign and one below the sign. In addition, the right-hand sign (from the wrong-way driver's point of view) contains two radar detectors, two cameras, and a cellular modem with antenna. One radar and camera face forward (toward the approaching wrong-way driver), and the other radar and camera face toward the side (to detect if the vehicle passes the first set of signs). The cellular modem provides text alerts and email notifications to the regional TMC through the manufacturer's software application for any wrong-way vehicles that pass the first set of signs, allowing the regional TMC operators to confirm the wrong-way vehicle and notify law enforcement (Al-Deek et al. 2015).

For the RFBs to be activated, a wrong-way vehicle must enter the range of the forward-facing radar (which is typically 100 ft). Once a wrong-way vehicle is detected by this

Table 19. Red RFB flash pattern.

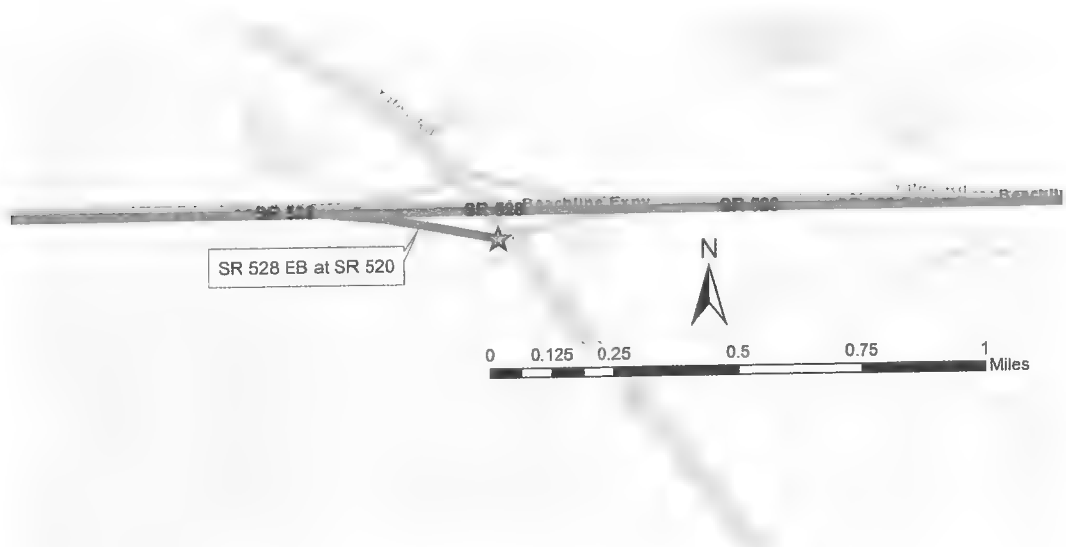
Cumulative Time in Milliseconds (ms)	Top Left	Top Right	Bottom Left	Bottom Right
100	X			X
200	X			X
300	X			X
400	X			X
500	X			X
600		X	X	
700		X	X	
800		X	X	
900		X	X	
1000 (1 second)		X	X	
On time (ms)	500	500	500	500
Percentage of cycle beacon is on	50%	50%	50%	50%

Note: X = beacon is on for 100 ms



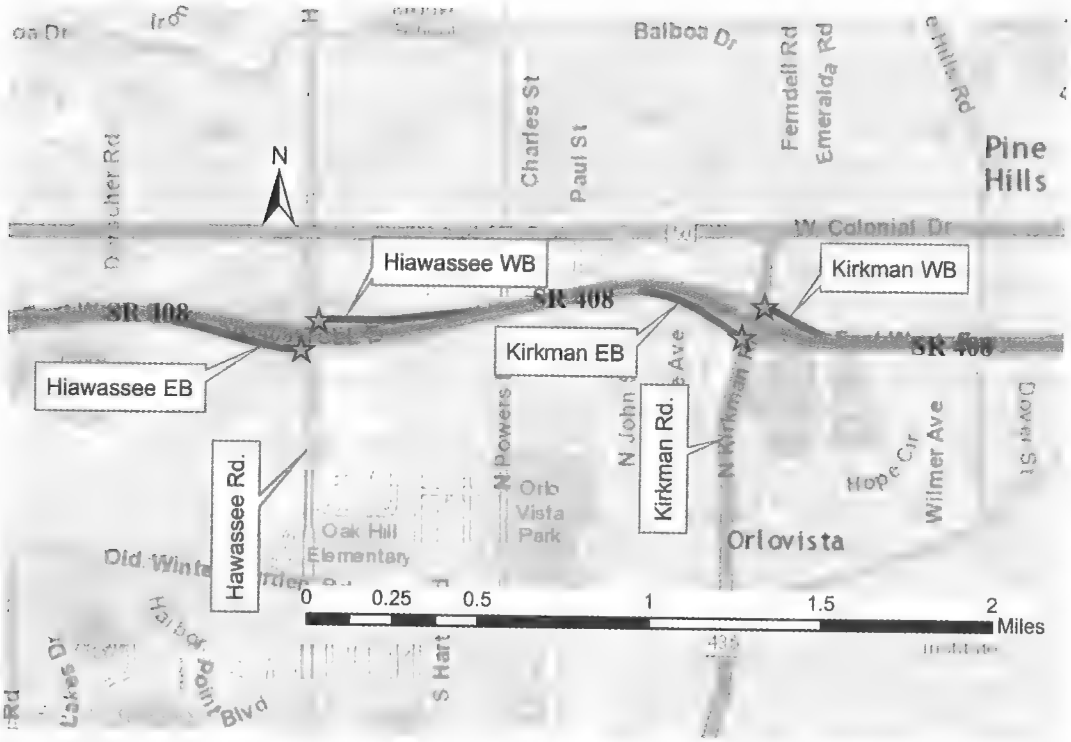
Source: University of Central Florida.

Figure 21. Red RFB pilot study sites.



Source: University of Central Florida.

Figure 22. SR 528 pilot study site details.

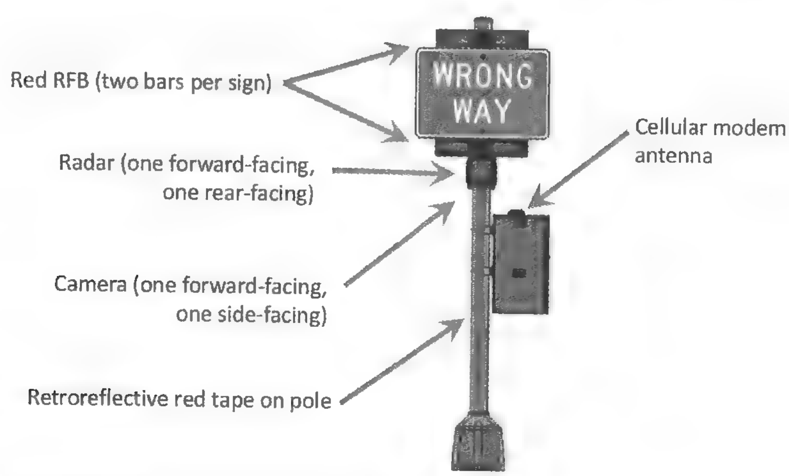


Source: University of Central Florida.

Figure 23. SR 408 pilot study site details.

radar, the RFBs on all four signs are activated and flash in a wig-wag pattern to get the wrong-way driver's attention. At the same time, the forward-facing camera (first camera) captures a series of images of the wrong-way vehicle. If the driver continues driving the wrong way past the first set of signs, the side radar detection zone is entered. Once this happens, the side camera (second camera) takes a series of images to confirm that the vehicle is still traveling the wrong way. The regional TMC is also alerted at this time via a text alert (Al-Deek et al. 2015).

Initial field testing of the red RFB WRONG WAY sign system and mainline detection in January 2015 found that there were some detection issues with the red RFB WRONG WAY sign system. The second camera had difficulty capturing images of small vehicles traveling at high speeds. UCF researchers suggested that modifications be made to the cameras to improve their reliability in capturing images of these vehicles. Eventually, additional tests in June 2015, fall 2015, and spring 2016 improved the accuracy for both the sign activation/first camera and second camera to 100 percent



Source: Central Florida Expressway Authority.

Figure 24. Red RFB WRONG WAY sign assembly components.

CHAPTER 4

Conclusion

Safety Analysis

In this report, researchers documented the results of multiple analyses focused on developing an improved understanding of WWD crash characteristics on divided highways as well as wrong-way countermeasure effectiveness on divided highways and freeways. An in-depth safety analysis of wrong-way crashes using a multistate dataset assessed the impact of median width and traffic control devices upon wrong-way crashes on high-speed divided highways. In addition, WWD event data were used to evaluate the effectiveness of LED border-illuminated WRONG WAY signs and red RFBs above and below WRONG WAY signs.

The findings from this research effort indicate that there is no one traffic control device that can reduce wrong-way movements across all of the circumstances studied (i.e., high-speed rural divided highways, high-speed urban divided highways, and freeways). In addition, the fidelity of the safety analysis did not allow researchers to assess the overall impact of the various combinations of traffic control devices. However, researchers were able to identify several traffic control devices that may be effective in reducing wrong-way movements on high-speed divided highways and freeways. In addition, the research team addressed several inconsistencies with regard to wrong-way movement traffic control in the MUTCD (discussed in Appendix B).

There are many factors that impact the operation of a divided highway crossing as one or two intersections. The median width is an important factor, but there are other factors as well. The manner in which the median width, median opening, median design, left-turn movements, and other factors interact could have a significant effect on the potential for wrong-way movements and were beyond the scope of this research project to analyze.

The 30-ft criterion used in the MUTCD and the UVC to distinguish crossing functions as one or two intersections has existed since at least the mid-1940s. However, there is no known rational basis for the use of 30 ft as the threshold criterion. The safety analysis conducted in this project found that there were numerous sites in the analysis where the traffic control devices did not fully comply with the MUTCD with respect to treating the location as one or two intersections. Primarily, this was represented in narrow medians (less than 30 ft) with STOP or YIELD signs in the median opening (6 percent) or in wide medians (greater than or equal to 30 ft) with no STOP or YIELD signs in the median opening (26 percent). This finding may be an indication that practitioners are using engineering judgment to determine the most effective installation of interior right-of-way devices to address safety and operations at divided highway crossings. There is also evidence from the safety analysis conducted in this project that the criterion may be 50 ft from a safety perspective. These findings led researchers to suggest changes to the definitions of median width and intersection in the MUTCD.

The safety analysis indicated that most wrong-way movements at divided highway crossings occurred when the driver turned left into the near-side roadway traveling in the wrong direction. The data indicated that this maneuver occurred for 90 percent of the wrong-way crashes for which the wrong-way entry point was specifically identified in crash documentation. The suggested changes to the MUTCD language focus on addressing this maneuver. Additional specific findings from the safety analysis pertinent to the suggested changes to the MUTCD language include the following:

- Greater use of ONE WAY signs (above those that are required) does not appear to deter wrong-way movements.
- There was limited evidence that use of the required divided highway sign on the crossroad exterior approaches deters wrong-way movement.
- The placement of DO NOT ENTER and WRONG WAY signs on the inside turn of a wrong-way movement (side of divided highway nearer the right-of-way line) does not deter wrong-way movements.
- Treatments that appear to deter wrong-way movements include:
  - DO NOT ENTER and WRONG WAY signs on the outside of a wrong-way turn,

- Wrong-way arrow markings for the through lanes on the divided highway,
- Presence of a centerline in the median opening, and
- Use of stop or yield lines when interior right-of-way treatments are provided.

Separate analysis of WWD event data support the use of flashing red LEDs within the border of WRONG WAY signs at freeway exit ramps. Therefore, researchers suggested changes to the MUTCD to allow red LEDs within the border of WRONG WAY signs. Early results from the red RFB WRONG WAY sign system pilot found that most of the errant drivers self-corrected before reaching the main lanes. These promising findings led to additional installations of the red RFB WRONG WAY systems at freeway exit ramps in central Florida. Additional data from these sites are needed before a detailed statistical analysis can be conducted and revisions for MUTCD language suggested.

Suggested Revisions

The findings from this research effort led to the development of proposed changes to the *2009 MUTCD* (FHWA 2012). Appendix C documents the researchers' reasoning for the changes and the detailed revisions. The following is a list of the MUTCD sections and figures included in the suggested revisions:

- Section 1A.13—Definition for "#94, Intersection"
- Section 1A.13—Definition for "#115, Median"
- Section 2B.09—YIELD Sign Applications
- Section 2A.23—Median Opening Treatments for Divided Highways with Wide Medians
- Section 2B.32—KEEP RIGHT and KEEP LEFT Signs
- Section 2B.37—DO NOT ENTER Sign
  - Figure 2B-12
- Section 2B.38—WRONG WAY Sign
- Section 2B.40—ONE WAY Signs
  - Figure 2B-15
  - Figure 2B-16
  - Figure 2B-17
- Section 2B.41—Wrong-Way Traffic Control at Interchange Ramps
- Section 2B.42—Divided Highway Crossing Signs
- Section 3B.20—Pavement Word, Symbol, and Arrow Markings
- Section 4C.01—Studies and Factors for Justifying Traffic Control Signals

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APPENDIX A

State of the Practice

In order to develop a comprehensive assessment of what is known from existing research with respect to the wrong-way driving (WWD) problem, its causes, and the development, implementation, and evaluation of wrong-way movement countermeasures, the research team conducted a literature review of domestic and international research. A summary of the findings from this effort are documented in this appendix.

Wrong-Way Crash Characteristics

Since the mid-1960s, many states in the United States have analyzed crash data to quantify the WWD problem and examine wrong-way crash characteristics. However, only a few past studies have focused on wrong-way crashes at the national level and in other countries. In addition, most of the previous research on WWD has focused on freeways. Below is a summary of the major findings related to the occurrence and severity of wrong-way crashes, the age and gender of the wrong-way driver, the role of driver impairment, the time of day in which wrong-way crashes occur, and the origination of the wrong-way movement.

Occurrence and Severity of Wrong-Way Crashes

Some of the earliest WWD research in the United States was conducted by the California Department of Transportation (Caltrans) in the mid-1960s. Tamburri and Theobald (1965) found that during two separate 9-month periods, there were approximately 1200 wrong-way events in California: 763 on freeways, 354 on expressways (i.e., divided highways), and 97 on conventional roads. Additionally, Tamburri and Theobald found that from 1961 to 1964, there was an average of 20 fatal wrong-way crashes on freeways. These fatal crashes resulted in an average of 31 deaths per year. When compared to all freeway and expressway crashes, Tamburri and Theobald found that wrong-way crashes were about six times more likely to produce a fatality.

In the 1980s, Copelan (1989) published an updated analysis of wrong-way crashes in California. In 1987, wrong-way crashes accounted for approximately 0.24 percent of all freeway crashes. In addition, about 3 percent of the fatal crashes on California freeways were attributed to wrong-way drivers. Over a 20-year period, the number of fatal wrong-way crashes had averaged 35 per year. This number remained relatively constant even though the number of miles of freeway and travel substantially increased during this time. Therefore, the fatal wrong-way crash rate had decreased. Copelan attributed the reduction to the many actions taken by Caltrans to combat WWD over the 20-year period, some of which will be discussed later in this appendix. Copelan also found that wrong-way crashes occurred more in urban areas than rural areas.

Vaswani (1973) found that in Virginia, wrong-way crashes only accounted for 0.1 percent of the total crashes, but the fatality rate per wrong-way crash was 30 times that for other types of crashes. Vaswani (1977a) also reviewed trends in wrong-way events and crashes from 1970 to 1976. During this time, a total of 114 wrong-way crashes, in which 54 people died and 120 were injured, occurred on interstate highways in Virginia. An additional 167 wrong-way crashes occurred on other four-lane, divided highways during the same period, killing 33 people and injuring 173 people. Although the number of wrong-way crashes was still relatively small compared to total crashes, they remained more severe. Similar to Vaswani's earlier study, the fatality rate per wrong-way crash was 31 times greater than for other types of crashes on interstate highways and 10 times greater than for other types of crashes on four-lane divided highways.

Two Texas studies (Cooner et al. 2004a; Finley et al. 2014) also confirmed that although wrong-way crashes represent less than 1 percent of all traffic crashes, they tend to be more severe and have a greater proportion that result in death or serious injury when compared with other types of crashes. In addition, these Texas studies and a study in Illinois (Zhou et al. 2012) found that urban areas have more wrong-way crashes than rural areas. Cooner et al. (2004a) also found

that most wrong-way collisions occurred in the leftmost (i.e., inside) lane of the correct direction. Similarly, the Illinois study reported statistics regarding which lane the wrong-way crash was in: 51 percent in the lane closest to the median (i.e., inside or left), 16 percent in the middle lane, 20 percent in the outside or right lane, and 8 percent on the shoulder. Another 7 percent occurred on a ramp.

A study of 110 wrong-way crashes on Michigan freeways during the 5-year period from 2005 to 2009 also found that wrong-way crashes were highly severe (Morena and Leix 2012). In 87 percent of the crashes, the wrong-way vehicle hit another vehicle traveling in the correct direction. The remaining crashes were single-vehicle crashes that involved the wrong-way vehicle only. The severity was also linked to the location of the crash. Only 6 percent of the crashes that occurred on an exit ramp resulted in a fatality or incapacitating injury. In contrast, 42 percent of the crashes on the main lanes resulted in a fatality or incapacitating injury.

A study in North Carolina for the 6-year period from 2000 to 2006 found that wrong-way crashes accounted for less than 0.2 percent of all freeway crashes (North Carolina DOT 2006). A similar study conducted with data from 2006 to 2012 yielded similar results (North Carolina DOT 2006). The latter study also found that 72 percent of all wrong-way crashes occurred on interstates and 52 percent happened in rural areas (North Carolina DOT 2006).

More recent studies in Florida (Kittelson & Associates, Inc. 2015) and Arizona (Simpson and Bruggeman 2015) also found that wrong-way crashes on freeways were more severe than other crashes on urban and rural freeways. In Florida, more than half of the wrong-way crashes resulted in injury and over 25 percent resulted in a fatality. In addition, approximately 76 percent of the wrong-way crashes on freeways occurred in urban areas compared to 24 percent in rural areas. In Arizona, 25 percent of all wrong-way crashes were fatal compared to 1 percent overall. Similarly, Zhang et al. (2016) found that on divided highways in Alabama, 12.5 percent of wrong-way crashes were fatal compared to 0.6 percent of all other crashes.

An analysis of wrong-way crashes from the Fatality Accident Reporting System (FARS) database from 1996 to 2000 (Moler 2002) revealed that 1753 people died in wrong-way crashes on U.S. freeways (ramps and main lanes). During the 5-year period, on average about 350 people were killed each year nationwide in wrong-way freeway crashes. Thousands more were injured.

In December of 2012, NTSB released a special investigation report on WWD on freeways and access ramps. This report documented the results of an analysis of fatal crash data in the United States from 2004 to 2009 and summarized nine NTSB wrong-way collision investigations. On average, 360 fatalities occurred each year from about 260 wrong-way crashes. Most of the wrong-way crashes occurred in the lane closest to the median (i.e., inside lane). NTSB concluded that although wrong-way crashes occur relatively infrequently (accounting for only about 3 percent of all crashes on freeways), they are more likely to result in fatal and serious injuries than other types of highway crashes because the vast majority are head-on collisions.

A more recent query of 8 years of crash data (2004 to 2011) from the FARS database (American Traffic Safety Services Association 2014; Baratian-Ghorghi et al. 2014) revealed that on average, 269 fatal wrong-way crashes continued to occur each year, resulting in 359 fatalities. These findings showed that these numbers remained steady even though the overall number of fatal crashes and fatalities decreased in the United States by more than 20 percent during the study period. On average, wrong-way fatalities account for about 2.3 percent of total fatalities on freeways. Further analysis on these data found that a higher proportion of wrong-way fatal crashes occur on urban roadways.

Wrong-way crash studies have also been conducted in other countries. A study performed by the Japanese Institute for Traffic Accident Research and Data Analysis (ITARDA 2002) found that less than 1 percent of crashes were caused by a wrong-way driver. However, 12 percent of the wrong-way crashes resulted in a death compared to 2 percent of total crashes. Similarly, studies in the Netherlands (SWOV Institute for Road Safety Research 2007) found that wrong-way crashes were less than 1 percent of all registered crashes, and that wrong-way crashes were rather severe. In another Japanese study (Xing 2013), researchers found that 62 percent of wrong-way crashes occurred in the median (i.e., inside) lane. The other lanes and shoulders accounted for 3 to 5 percent of the crashes. An additional 19 percent happened on ramps at interchanges, junctions, and rest areas. In France (Kemel 2015), wrong-way crashes represented 1 percent of all injury crashes and 6 percent of fatalities. Wrong-way crashes were also six times more likely to be fatal than other crashes.

Overall, wrong-way crashes represent a small portion of the total crashes on U.S. freeways and divided highways. However, these crashes result in more fatalities than other types of crashes on these facilities because most are head-on collisions. Wrong-way crashes tend to occur more in urban areas than rural areas, and most tend to take place in the lane closest to the median (i.e., inside lane).

Wrong-Way Driver Characteristics

Gender and Age

Tamburri and Theobald (1965) were some of the first researchers to investigate the characteristics of the wrong-way driver. They found that 80 percent of the wrong-way drivers in California were male, and that the rate of WWD per vehicle miles traveled increased with age. Lew (1971) also reported on the age of the California wrong-way driver. He found that drivers 16 to 19 years old were underrepresented

in wrong-way driving crashes and those 70 to 79 years old were over twice the number expected based on their proportion of the driving population.

More recently, two Texas studies (Cooner et al. 2004a; Finley et al. 2014), a New Mexico study (Lathrop et al. 2010), a Michigan study (Morena and Leix 2012), an Illinois study (Zhou et al. 2012), and an Alabama study (Pour-Rouholamin et al. 2016) confirmed that most of the wrong-way crashes still involved a male driver (59 to 77 percent). As with previous studies, the percentage of Texas, Michigan, Illinois, and Alabama drivers over 65 years old involved in wrong-way crashes was higher compared to their involvement in other types of crashes. In addition, almost half of the wrong-way drivers in Texas were 16 to 34 years old. Furthermore, in Michigan and North Carolina (North Carolina DOT 2006), nearly one-quarter of the wrong-way drivers were under the age of 25 or 20 to 29 years old, respectively. In Illinois, Zhou et al. (2012) found that younger drivers (under the age of 25) were also proportionally overrepresented.

In Florida (Kittelson & Associates, Inc. 2015), although drivers less than 30 years old accounted for 42 percent of the wrong-way crashes on freeways, this proportion was similar to all freeway crashes for this age group. In contrast, older drivers (≥ 75 years old) accounted for about 5 percent of the wrong-way crashes on freeways. This proportion was more than three times the expected proportion from statewide trends on freeways.

On divided highways in Alabama, Zhang et al. (2016) found that drivers less than 44 years old accounted for approximately 47 percent of the wrong-way crashes. However, this proportion was similar to all other divided highway crashes for this age group. In contrast, drivers over 65 years old accounted for approximately 27 percent of the wrong-way crashes on divided highways. However, this proportion was more than two times the proportion for all other crashes on divided highways.

A query of 8 years of crash data (2004 to 2011) from the FARS database (Baratian-Ghorghi et al. 2014) found that male wrong-way drivers outnumbered female wrong-way drivers by more than 2 to 1. About 15 percent of the wrong-way drivers were age 65 or older. Comparing this to the 10 percent of older drivers involved in other freeway crashes showed that older drivers are overrepresented in wrong-way fatal crashes. The NTSB (2012) report also noted findings that drivers over the age of 70 are overrepresented in wrong-way crashes.

A study performed by ITARDA (2002) in Japan determined that the following age groups were overrepresented in wrong-way crashes: 25 to 29, 45 to 54, and 75 to 79. Furthermore, 29 percent of the wrong-way crashes on highways involving injury or death were caused by senior citizens. A more recent Japanese study (Xing 2013) found that approximately half of the wrong-way drivers were more than 65 years old, and 40 percent were over 70 years old. Studies in the Netherlands (SWOV Institute for Road Safety Research 2007) also found that drivers at least 70 years old were 23 times more likely than other age groups to be involved in a wrong-way crash. In France (Kemel 2015), drivers over the age of 65 were also overrepresented in wrong-way crashes, and male drivers accounted for approximately 75 percent of the wrong-way crashes.

Overall, male drivers tend to be involved in wrong-way crashes more than female drivers. Many studies also found that younger drivers and senior citizens tend to be proportionally overrepresented in wrong-way crashes.

Driver Impairment

Tamburri and Theobald's (1965) study also revealed that approximately one-third of all the wrong-way drivers in California had been drinking. Of those who had been drinking, most (58.6 percent) were 30 to 49 years old. In the 1980s, Copelan (1989) found that almost 60 percent of all wrong-way crashes and 77 percent of fatal wrong-way crashes in California were caused by a driver who was impaired by drugs or alcohol. An analysis of wrong-way crashes in Indiana from 1970 to 1972 showed that approximately 55 percent of the drivers were impaired (Scifres and Loutzenheiser 1975). Similarly, a 1977 Virginia study (Vaswani 1977a) found that 53 percent of the wrong-way drivers on interstates and 33 percent of the wrong-way drivers on non-interstate, four-lane, divided highways were driving under the influence. Furthermore, a Washington State DOT study (Moler 2002) indicated that half of the 30 wrong-way crashes along an interstate corridor were alcohol or drug related. From 1983 to 1990 in the Netherlands (SWOV Institute for Road Safety Research 2007), alcohol was involved in 45 percent of the wrong-way crashes. However, this percentage decreased to 20 percent from 1991 to 1998. Over the whole period (1983 to 1998), 56 percent of the wrong-way drivers 25 to 54 years old were under the influence of alcohol.

A 2004 Texas study (Cooner et al. 2004a) found that almost 61 percent of all the wrong-way crashes on freeways had some influence of alcohol and/or drugs cited. In 2013, Finley et al. (2014) investigated the blood alcohol concentration (BAC) level of wrong-way drivers in Texas that were tested for alcohol. Key findings regarding impairment were:

- Almost 90 percent had a BAC level equal to or greater than the legal limit (0.08 g/dL).
- Approximately 50 percent had a BAC level equal to or greater than twice the legal limit (0.16 g/dL).
- Approximately 10 percent had a BAC level equal to or greater than three times the legal limit (0.24 g/dL).
- The BAC ranges with the highest percentage of drivers (30 percent) were 0.16 to 0.199 g/dL and 0.20 to 0.239 g/dL.
- Most drivers (60 percent) had a BAC level of 0.16 to 0.239 g/dL.

- The average BAC level was 0.18 g/dL (over twice the legal limit).

Many other states have also found alcohol to be a major contributing factor for wrong-way crashes on freeways. In Arizona, impaired drivers were the cause of 65 percent of all wrong-way crashes (Simpson and Bruggeman 2015). In Michigan, nearly 60 percent of the wrong-way drivers for which the impairment was known were under the influence of either alcohol or drugs (Morena and Leix 2012). Similarly, in New Mexico, 63 percent of the wrong-way drivers tested had a BAC level above the legal limit (0.08 g/dL) (Lathrop et al. 2010). In North Carolina (North Carolina DOT 2006), 48 percent of all wrong-way crashes were alcohol related. An Illinois study (Zhou et al. 2012) found that 50 percent of the wrong-way drivers were under the influence of alcohol and 5 percent were under the influence of drugs. Furthermore, 80 percent of the drivers completing a test for alcohol and drugs had a BAC level greater than 0.1 g/dL. In Florida, alcohol and/or drug use was involved in 45 percent of the wrong-way crashes on freeways (Kittelson & Associates, Inc. 2015). In Alabama, almost half of the wrong-way drivers were intoxicated (Pour-Rouholamin et al. 2016).

For divided highways in Alabama, Zhang et al. (2016) found that driving under the influence was a contributing factor in only 23 percent of wrong-way crashes. However, this proportion was more than seven times the proportion for all other crashes on divided highways.

The NTSB (2012) report revealed that approximately 60 percent of fatal wrong-way crashes involved alcohol. Furthermore, in seven of the nine wrong-way crashes investigated by NTSB, the wrong-way driver had BAC over 0.15 g/dL. A more recent query of 8 years of crash data (2004 to 2011) from the FARS database (Baratian-Ghorghi et al. 2014) found that on average, 58 percent of wrong-way crashes in the United States were related to driving under the influence of alcohol and/or drugs. This was nearly twice the rate of alcohol or drug involvement for all fatal crashes. Furthermore, impaired male wrong-way drivers outnumbered impaired female wrong-way drivers by nearly 3 to 1. Nearly two-thirds of the wrong-way drivers under the age of 65 were impaired by alcohol or drugs.

Overall, driving under the influence of alcohol and/or drugs is the primary contributing factor in most of the wrong-way crashes. Impaired wrong-way drivers involved in crashes tend to be younger and have BAC levels that exceed the legal limit by two to three times (i.e., 0.16 to 0.239 g/dL).

Time-of-Day Characteristics

In the 1960s, Tamburri and Theobald (1965) found that in California, WWD events peaked at 11:00 a.m. and again at 2:00 a.m. The late morning peak was attributed to drivers over 60 years old, while the early morning peak coincided with the typical time for establishments that serve alcohol to close in California. Likewise, both Japanese studies (ITARDA 2002; Xing 2013) found that most crashes involving senior citizens occurred during the day and most crashes involving the other age groups occurred at night.

In the 1980s, Copelan (1989) found that the number of WWD crashes was higher at night than during the day and confirmed that wrong-way crashes in California still peaked at 2:00 a.m. Two studies in Texas (Cooner et al. 2004a; Finley et al. 2014) also identified a peak in wrong-way crashes on freeways around the typical closing time for establishments that serve alcohol. These two Texas studies also found that more than half of the wrong-way crashes occurred between midnight and 6:00 a.m. This finding led Cooner et al. (2004a) to conclude that wrong-way crashes on freeways were five times more likely to occur during the early morning hours. Studies in North Carolina (North Carolina DOT 2006), New Mexico (Lathrop et al. 2010), Michigan (Morena and Leix 2012), Florida (Kittelson & Associates, Inc. 2015), Arizona (Simpson and Bruggeman 2015), and Alabama (Pour-Rouholamin et al. 2016) identified similar trends with respect to time of day. Many state studies have also found that wrong-way crashes on freeways occur most frequently at night on the weekend (e.g., Scifres and Loutzenheiser 1975; Zhou et al. 2012; Finley et al. 2014; Kittelson & Associates, Inc. 2015). For the United States, the NTSB (2012) report noted that fatal wrong-way crashes on freeways occurred more frequently at night (78 percent) and on the weekend (57 percent). Zhang et al. (2016) found that most of the wrong-way crashes on divided highways in Alabama occurred in the evening (6:00 p.m. to midnight, 46 percent) and at night (midnight to 6:00 a.m., 20 percent).

Overall, many daytime wrong-way crashes are caused by senior citizens, while those occurring at night are attributed to other age groups and involve driving under the influence of alcohol and/or drugs. All studies seem to suggest that wrong-way crashes are more prevalent at night during the early morning hours.

Origin of Wrong-Way Movement

In California, Tamburri and Theobald (1965) found that on freeways, 53 percent of the events began when a driver entered the freeway via an exit ramp. Other drivers made a U-turn on the main lanes (19 percent), made a U-turn from the on-ramp (9 percent), or drove across the median (4 percent). On freeways, the origin of a wrong-way maneuver most frequently occurred at diamond interchanges (38 percent), although the researchers noted that this was the most common type of ramp in California at that time.

Copelan's (1989) review of the California data and countermeasure implementation from the 1960s to the 1980s revealed that cul-de-sac, button hook, trumpet, and two-quadrant

cloverleaf interchanges had a greater number of wrong-way crashes than other types of interchanges. California studies also found that left exits appeared to be on-ramps to some wrong-way drivers.

In Virginia, Vaswani (1977a) found that about 50 percent of the wrong-way entries onto an interstate highway originated at interchanges. Another 15 percent originated at crossovers and rest areas or were associated with U-turns and median crossings. Vaswani (1973) also found that most wrong-way entries were at partial interchanges of the diamond type.

The NTSB (2012) report also noted that entering an exit ramp in the wrong direction was the primary origin of wrong-way movements onto freeways. Other actions resulting in wrong-way movements included making U-turns on the main lanes of the freeway and using an emergency turn-around through the median.

Parsonson and Marks (1979) determined that the half-diamond, partial cloverleaf loop ramp, and partial cloverleaf AB loop ramp had the highest wrong-way entry rates. These researchers found that since half-diamonds are incomplete, drivers often made intentional wrong-way maneuvers at these types of interchanges. The main issue identified with the partial cloverleaf designs was that the entrance and exit ramps are in close proximity to each other.

Cooner et al. (2004a) gathered data on the locations where 323 freeway-related wrong-way crashes originated from crash reports. These researchers found that they could only deduce the entry point for about one out of every three crashes. Even so, the researchers were able to note several important characteristics about wrong-way crashes.

- Several locations with left-side exit ramps experienced multiple wrong-way crashes.
- Several locations where a one-way street transitions directly into a freeway section resulted in multiple wrong-way crashes.
- Almost 4 percent of the wrong-way crashes were the result of a driver making a U-turn on the main lanes.

In New Mexico, Lathrop et al. (2010) could only determine the origination of the wrong-way maneuver for 12 out of 49 wrong-way collisions. Five of the drivers entered the interstate the wrong way by driving up an exit ramp, four of the drivers made a U-turn on the main lanes, and three of the drivers entered from external highway/nonstandard entrance points.

In Michigan, Morena and Leix (2012) were able to confirm that 31 out of 110 crashes entered at a specific exit ramp since the collision occurred at the same ramp. In addition, the reporting officer was able to identify the point of entry for four main lane crashes. For all the other crashes, the point of origin was unknown. Using the known entry points, Morena and Leix reviewed the type of interchange and offered educated commentary on the potential driver confusion issues that could have led to the wrong-way entry. Their review confirmed previous study findings about the potential confusion at partial cloverleaf designs. This type of interchange design was involved in 60 percent of the known wrong-way entry points, even though they only account for 21 percent of the interchanges in Michigan. The main culprit is the pair of freeway exit and entrance ramps that are adjacent and parallel to each other and intersect with the cross street at a 90-degree angle. Disoriented, distracted, or impaired drivers can mistakenly turn onto the exit ramp instead of the entrance ramp. Morena and Leix also found that trumpet interchanges experienced 11 percent of the wrong-way entries but only comprised 3 percent of the interchanges in Michigan.

In Illinois, Zhou et al. (2012) confirmed how difficult it is to identify the wrong-way entry point from crash report narratives. Only 20 percent of the wrong-way crashes had wrong-way entry points recorded in the reports. For all other crashes, the researchers had to estimate the wrong-way entry point. For the 47 known origins, 14 began with a driver making a U-turn on a freeway. Compressed diamond and diamond interchanges resulted in 26 percent and 34 percent of the known wrong-way entries, respectively. Partial cloverleaf interchanges were connected with 11 percent of the known entries.

With respect to divided highways, Tamburri and Theobald (1965) found that approximately half of the California crashes originated at intersections with median openings. However, some wrong-way maneuvers (6 percent) occurred at intersections without median openings (i.e., only right turns permitted). Furthermore, 19 percent of the drivers traveled through the median (not at an intersection) and 19 percent made a U-turn on the main lanes.

Vaswani (1977a) found that on non-interstate, four-lane, divided highways in Virginia, about 40 percent of the wrong-way entries occurred at intersections with crossroads or exit ramps connecting with interstate routes. Another 25 percent happened when the driver exited from a business establishment. About 20 percent occurred at crossovers, the beginning of divided sections, and construction sites or were associated with U-turns and median crossings.

Beginning in 2013, the Iowa department of transportation piloted the use of high definition radars and video analytics to detect wrong-way vehicles. Findings from this effort showed 68 percent of the 51 confirmed wrong-way events entered via at-grade intersections on divided highways. The most common wrong-way entry path was a vehicle turning left from an intersecting roadway into the near main lanes (Athey Creek Consultants 2016).

Overall, identifying the location of a wrong-way entry is difficult. Nevertheless, many studies have found that most

of the wrong-way movements on freeways originate at exit ramps. Wrong-way maneuvers on freeways also occur from drivers making U-turns on the main lanes, traveling across the median, and entering from a nonstandard entrance point. Most wrong-way entries on divided highways occur at intersections with median openings. However, they also happen at intersections without median openings and from drivers making U-turns on the main lanes or driving through the median. Several types of interchange designs have been found to be more susceptible to wrong-way entries. The side-by-side entrance and exit ramp configuration of partial cloverleaf interchanges may cause drivers to unintentionally turn into the exit ramp instead of the entrance ramp. Other incomplete or partial interchanges may lead to intentional wrong-way maneuvers. In addition, in some cases, drivers mistake an exit ramp at a diamond interchange as a two-way frontage road that runs parallel to the main lanes. Left-side exit ramps are also more susceptible to wrong-way entries.

Other Contributing Factors for Wrong-Way Crashes

As discussed previously, many studies have identified driving under the influence of alcohol and/or drugs, older drivers, and interchange design as factors that contribute to wrong-way crashes. Other contributing factors include intentional behavior (e.g., suicide, avoiding congestion, or missed exit), driver inattention, driver confusion, physical or mental illness, insufficient lighting, insufficient sight distance, and inclement weather (Zhou et al. 2012).

Wrong-Way Crash Countermeasures

Common countermeasures for WWD include traffic control devices (signs and pavement markings), intelligent transportation systems (ITSs), and geometric modifications (e.g., access management and interchange reconstruction). Enforcement and education are also tools that can be used to mitigate WWD. In the future, connected vehicle applications will also be used to detect and alert wrong-way drivers, right-way vehicles in the path of the wrong-way driver, enforcement, traffic management centers, and other entities through the use of vehicle-to-infrastructure and/or vehicle-to-vehicle technologies. With respect to the objectives of this project, the research team focused the literature review on traffic control devices and associated ITS/technology systems.

In the mid-1960s, Caltrans research also involved identifying wrong-way countermeasures. Caltrans examined the use of preventive measures including the spike strip on exit ramps and a detection and warning system that featured a WRONG WAY sign that was automatically illuminated when a wrong-way vehicle was detected on an exit ramp in conjunction with an electric horn warning to alert the WWD driver (Tamburri and Theobald 1965; Doty and Ledbetter 1965; Tamburri 1965). Caltrans staff concluded that spike strips:

- Were not a safe and viable countermeasure because they disabled but did not stop a wrong-way vehicle,
- Could create a hazard when spikes were broken,
- Were an ongoing maintenance concern to ensure proper operation, and
- Could be misinterpreted by right-way drivers as a hazard.

In the 1970s, Caltrans examined a modified form of the wrong-way vehicle detection system it originally developed in the late 1960s (Rinde 1978). Caltrans placed this system in over 4000 freeway exit ramp locations throughout California to assess which ramp designs and other factors were associated with wrong-way driving. This research showed that the following changes to the standard exit ramp signing were effective in reducing wrong-way entries onto freeways to less than or equal to two per month at 90 percent of the ramps identified as having a significant wrong-way entry problem:

- The bottom of the lower portion of the wrong-way movement sign package (WRONG WAY sign mounted below a DO NOT ENTER sign on the same post) was placed 2 ft above the edge of the pavement.
- At least one wrong-way movement sign package was placed in the area covered by a vehicle's headlights and visible to drivers from all approaches.
- ONE WAY signs were mounted 1.5 ft above the pavement.
- FREEWAY ENTRANCE signs were placed as close as possible to the intersection of the ramp and cross street.

While this research has been used to encourage the use of a lower mounting height for DO NOT ENTER and WRONG WAY signs, the positive findings were a result of the implementation of a combination of traffic control devices, not just lowered signs. Similarly, the Georgia Department of Transportation sponsored research in the late 1970s that used the wrong-way camera system from Caltrans in a study to monitor exit ramps in order to correlate various ramp designs with WWD activity (Parsonson and Marks 1979).

The first research regarding WWD in Texas occurred from the late 1960s to the early 1970s. Texas A&M Transportation Institute (TTI) researchers conducted a survey of state and local highway engineers and law enforcement personnel in an attempt to qualitatively determine the nature of WWD in Texas (Messer et al. 1971). Researchers also summarized the state of the knowledge on WWD on freeways and expressways, including a review of countermeasures and the development of a detection and communication system to warn drivers of WWD (Friebele et al. 1971).

As discussed previously, in the mid-1970s, the Virginia Transportation Research Council (VTRC) conducted research

to identify the causes of wrong-way movements (Vaswani 1973, 1977a). VTRC also developed countermeasures to address the causes identified. The countermeasures were mainly directed at exit ramp configurations and included improved pavement markings that used reflectorized wrong-way pavement arrows on all exit ramps, implementation of sensors on exit ramps for detecting WWD in future construction projects, and consideration of lowered DO NOT ENTER and WRONG WAY signing to address alcohol and nighttime problem locations.

Vaswani (1977b) also experimented with divided highway crossing signs on the minor approaches to an intersection with a divided highway. According to Vaswani, the Delaware Department of Highways and Transportation had successfully used this sign for 20 years to mitigate wrong-way maneuvers. The field observations in Virginia found nine wrong-way entries during the 3 years of before data and no wrong-way entries in the 7-month after period. Although the after evaluation period was too short to allow for definite conclusions, the results were encouraging.

In the 1980s, the Illinois DOT experimented with sensors embedded in the roadway to detect wrong-way traffic movement, which, if activated, would lower a signal arm across the road and initiate a dynamic message sign (DMS) to alert exiting traffic about the WWD hazard ahead (Knight 1983). In New Mexico in the 1990s, a directional traffic sensor system was implemented on an exit ramp near Albuquerque. This system used loop sensors that detected wrong-way vehicles and activated red flashers on a WRONG WAY sign to warn the wrong-way driver. Additionally, yellow flashers on a STOP AHEAD sign for right-way ramp vehicles were used to warn traffic of an exit ramp obstacle (Cooner et al. 2004a).

In the 2000s, the Washington State DOT used video monitoring systems on select exit ramps to detect wrong-way drivers. When a wrong-way vehicle was detected, a blank-out sign with the message WRONG WAY and flashers were activated. Concurrently, the system videotaped the vehicle's movements and the driver's behavior to further assess the problem (Moler 2002).

In 2003, the Texas DOT sponsored WWD research following several severe wrong-way crashes around the state (Cooner et al. 2004a, 2004b). The major findings from the research called for the use of reflectorized wrong-way arrows on exit ramps, lowered DO NOT ENTER and WRONG WAY signs mounted together on the same sign support, and development of a field checklist for wrong-way entry problem locations.

In 2005, Schrock et al. conducted a before-after study to determine if lane direction arrows on a two-way frontage road reduced the number of wrong-way maneuvers. In the before period, these researchers found that one of every 13 drivers exiting the freeway onto the frontage road incorrectly used the left lane for travel. In the after period, only one of 150 vehicles used the incorrect lane. Overall, these researchers found a 90 percent reduction in the number of wrong-way maneuvers.

In 2006, a wrong-way detection system was implemented on the Pensacola Bay Bridge in Florida (Williams 2007). This system used a low-power microwave radar detector that was not affected by adverse weather conditions. The detector was mounted approximately 20 ft above the roadway and could detect a wrong-way movement at approximately 1000 ft prior to the bridge. When a wrong-way movement was detected, flashing beacons visibly enhanced the DO NOT ENTER and WRONG WAY signs above the travel way.

In October 2008, the Harris County Toll Road Authority (HCTRA) began to operate a wrong-way driver detection system on a 13.2-mi portion of the West Park Tollway, a controlled-access roadway in Houston. The system used Doppler radar detection sensors supplemented with in-pavement loop sensors at 14 points along the tollway. Incident management center (IMC) personnel received all wrong-way movement detections and monitored the system 24 hours a day and 7 days a week. Once a vehicle was detected, operators at the IMC could immediately dispatch law enforcement officers, monitor the vehicle's whereabouts via closed-circuit television (CCTV) and a geographic information system wrong-way detection map integrated into the software platform, and warn other motorists of the detected wrong-way vehicle using DMSs. This deployment was the first of its type in the United States and incorporated a number of innovative aspects including site-specific design, configuration, and communications dispatch and response protocols (ITS International 2010). The original cost in 2007 was $337,000 (about $25,530 per mile).

In 2011, HCTRA spent an additional $175,000 to enhance the system, which increased the cost per mile to approximately $38,788. Additional features included:

- Once the alarm is activated, the nearest CCTV camera automatically pans toward the detection site so that IMC dispatchers can track a wrong-way vehicle and relay information to first responders.
- Warning messages conveyed to other drivers on DMSs can be displayed in automated incident response plans based on the direction of travel and location of the detection.
- Light-emitting diode (LED) in-ground lighting was installed to warn motorists at South Post Oak and Richmond Avenue.
- WRONG WAY signs with flashing LEDs around the border were installed at locations that have a higher rate of incidents.
- Through attrition, in-ground puck loop systems are replacing radar sensors.

Finley et al. (2014) reviewed the WWD alerts received by the HCTRA system from 2009 to 2013. Most of the verified

WWD alerts showed that the driver self-corrected (74 percent). Law enforcement caught only about 13 percent of the wrong-way drivers that resulted in an alert. Of these, two-thirds of the drivers were arrested for driving while intoxicated. The HCTRA detection system alert review also revealed that about 7 percent of the alerts were the result of a reversing down the roadway. In most instances, this appeared to occur because the driver missed the exit.

Finley et al. (2014) also examined the HCTRA WWD alert data to determine the effectiveness of the flashing LED in-pavement lighting and WRONG WAY signs with flashing red LEDs around the border at South Post Oak. A before-after evaluation of these two devices could not be completed since the addition of the puck sensors (also in 2011) increased the number of overall alerts received. Even so, the HCTRA data did show that out of the 62 WWD alerts received for this location between January 2012 and December 2013, 86 percent of the drivers self-corrected before reaching the main lanes.

In 2009, in response to wrong-way crashes on the Dallas North Tollway, the North Texas Tollway Authority (NTTA) formed a WWD task force and deployed a number of signing and marking countermeasures, including wrong-way pavement markings created with retroreflective raised pavement markers (RRPMs) at every exit ramp and red retroreflective sheeting on exit ramp sign supports (November 2009). Further countermeasure implementation included:

- WRONG WAY signing with flashing red LEDs around the border at three exit ramp locations in December 2010. These signs flash continuously (i.e., day and night).
- Pavement marking and signing modifications at cross street approaches at problem locations (January 2011 at Wycliff Avenue and June 2012 at the south end of the Dallas North Tollway). With respect to diamond interchanges, NTTA replaced left-turn arrows with through-lane-use arrows when the left-turn lane for the exit ramp extended back beyond the entrance ramp.

Based on previous research recommendations (Cooner et al. 2004a) and success in other states (notably California), NTTA also considered the use of lowered DO NOT ENTER and WRONG WAY signing. Although NTTA was aware that a 3-ft mounting height was an option, it was unable to locate any crash tests to verify that signs at this height would not be hazardous to an errant vehicle that was traveling the right way on the system. TTI researchers also had concerns regarding how a sign mounted at 3 ft would perform using the latest crash test criteria in the AASHTO *Manual for Assessing Safety Hardware* (MASH) (2009). In addition, modeling revealed that a sign mounted at 2 ft was almost twice as bright as a sign mounted at 3 ft. Thus, the 2-ft mounting height (measured vertically from the bottom of the sign to the elevation of the near edge of the pavement) was proposed as a height capable of catching an impaired driver's attention while still being able to alert unimpaired drivers of restricted movements and meet current crashworthiness criteria. Using standard 36-inch by 36-inch DO NOT ENTER signs and 24-inch by 36-inch WRONG WAY signs, the sign assemblies had a total height of 5 ft and 4 ft, respectively (measured vertically from the top of the sign to the elevation of the near edge of the pavement).

NTTA contracted with TTI to determine if the 2-ft sign assemblies described above would meet the provisions of the AASHTO MASH. The testing was conducted, and the findings were submitted to the FHWA Office of Safety for review. On December 7, 2010, NTTA received a letter from FHWA stating that the 24-inch by 36-inch WRONG WAY sign mounted 2 ft above the ground was acceptable to use on the National Highway System under the provisions of the AASHTO MASH. In January 2011, TTI completed a crash test on a 36-inch by 36-inch DO NOT ENTER sign mounted at a 2-ft height. The results showed that the test assembly and sign passed.

In spring 2011, NTTA, in cooperation with Texas DOT, requested experimentation to mount 36-inch by 36-inch DO NOT ENTER and 24-inch by 36-inch WRONG WAY signs at 2 ft instead of the standard 7-ft mounting height. FHWA approved this request on July 14, 2011.

At that time, NTTA had 142 exit ramps on its system; of these, 51 were tolled (meaning they had in-ground loops sending wrong-way driver alerts to the command center). NTTA decided to install lowered signs at 28 exit ramps (11 tolled and 17 non-tolled locations) based on the frequency of WWD events, geometry of the ramp, presence of pedestrians, and desire to have system-wide coverage. NTTA implemented the following three configurations of the DO NOT ENTER and WRONG WAY signage to accommodate pedestrian and cross-traffic visibility concerns:

- Configuration 1: DO NOT ENTER sign at the 2-ft mounting height and WRONG WAY sign at the standard 7-ft mounting height. This configuration was installed at 12 locations.
- Configuration 2: DO NOT ENTER sign at the standard 7-ft mounting height and WRONG WAY sign at the 2-ft mounting height. This configuration was installed at two locations.
- Configuration 3: DO NOT ENTER and WRONG WAY signs both at the 2-ft mounting height. This configuration was installed at 14 locations.

At the remaining 114 exit ramps in the NTTA system (40 tolled and 74 non-tolled), the DO NOT ENTER and WRONG WAY signs remained at the standard height (7 ft). The standard configuration served as a control group during the evaluation period.

Finley et al. (2014) used WWD event data collected by NTTA from August 2010 to July 2013 to conduct an initial

analysis regarding the effectiveness of the lowered signs. However, the limited sample size produced statistically insignificant results. An updated analysis in 2015 (Finley et al. 2016b) found a 56 percent reduction in WWD events after the installation of lowered signing. In other words, the WWD events at the exit ramps with lowered signing were cut in half. This percent change was statistically significant at a 5 percent significance level, and the 95 percent confidence interval ranged from an 85 percent reduction to a 27 percent reduction. The analysis method used accounted for changes in events due to factors other than the lowered signing (e.g., traffic volumes), but it did not account for regression to the mean, which may have occurred since NTTA installed lowered signing at some ramps with high frequencies of WWD events. Thus, the analysis may overestimate the effectiveness of lowered signing at sites with an average WWD event history.

In May 2011, public transportation and law enforcement agencies in the San Antonio area created a WWD task force to share information and identify means to address and reduce WWD activity. The task force used various methods to document WWD activity in San Antonio, with the purpose of identifying where WWD countermeasure deployment would be most meaningful and effective. After analyzing the various WWD event data sources and the information details available from each source, analysts determined that insufficient information existed to link WWD events with specific freeway ramps where wrong-way drivers entered the freeway network. Accordingly, there was no logical means that could be devised for prioritizing the treatment of one freeway ramp over another. Thus, the task force concluded that treatment of an entire freeway corridor was necessary in order to determine the effectiveness of WWD countermeasures.

The task force selected the 15-mi US 281 corridor from I-35 (near downtown) to just north of Loop 1604 (the far north central side of San Antonio) as the Wrong-Way Driver Countermeasure Operational Test Corridor. Between March 2012 and June 2012, Texas DOT staff and contractors installed WRONG WAY signs with flashing red LEDs around the border at each exit ramp in the US 281 test corridor. The purpose of the flashing red LEDs was to increase the conspicuity of WRONG WAY signing at night. The signs were set to flash under low ambient light conditions (i.e., at night and during some inclement weather events), whether or not a wrong-way vehicle was detected. Texas DOT felt that this operation would catch the attention of a wrong-way driver approaching on the frontage farther away instead of waiting until he or she was driving up the ramp. Also, sustained false alarm issues with the detection equipment led to deactivation of the detection component.

Where the length and design of the exit ramp allowed, WRONG WAY signs with flashing red LEDs around the border supplemented the existing, static WRONG WAY signs. On shorter ramps, the WRONG WAY signs with flashing red LEDs around the border replaced the existing static WRONG WAY signing. The battery for the signs was encased in the sign pole and charged by a small solar array attached to the top of the sign support.

Even before the task force was created, the San Antonio Police Department (SAPD) and Texas DOT implemented several procedures with regard to responding to WWD events. In August 2010, SAPD began to use an emergency call signal (i.e., E-tone) for its radio network when a wrong-way driver was reported to 911. In January 2011, SAPD implemented a code in its computer-aided dispatch (CAD) system that specifically identified all wrong-way driver events. Similarly, in March 2011, Texas DOT TransGuide traffic management center (TMC) operators began logging all WWD events, not just those that resulted in a crash. In May 2011, Texas DOT TransGuide operators began displaying wrong-way driver warning messages on DMSs when an E-tone was issued (previously they waited to display warning message until the wrong-way driver was visually verified). Two of these procedures (code in the SAPD CAD system and Texas DOT logging all WWD events) created databases that could be used to determine the WWD trends in San Antonio. Institutional actions also included site reviews of select freeway exit ramps around San Antonio, an ongoing effort that involves staff from Texas DOT, the City of San Antonio Public Works Department, and TTI, and employs a site review checklist developed during previous research (Cooner et al. 2004a).

Finley et al. (2014) used the WWD subcomponent of SAPD 911 call log data to determine the effectiveness of the LED border-illuminated WRONG WAY signs. Using 14 months of before data and 22 months of after data, TTI researchers found a 38 percent reduction in WWD events on the US 281 corridor after the installation of the LED border-illuminated WRONG WAY signs. This percent change was statistically significant at a 5 percent significance level (the 95 percent confidence interval ranged from a 63 percent reduction to a 13 percent reduction).

Finley et al. (2014) also reviewed the Texas DOT TransGuide operator log data and found that for 87 percent of the WWD events documented since March 2011, there was no crash or the driver of the vehicle was not apprehended. Of those WWD events where the driver was apprehended or a crash occurred (92), 67 percent were attributed to alcohol impairment and approximately 1 percent were disoriented elderly drivers. For over three-quarters of the WWD events, Texas DOT was able to post a WWD warning message on at least one DMS in the area. This message warned drivers of the potential for a wrong-way driver in the area.

While extensive human factors and traffic operations research on DMS message design has been previously conducted, these efforts have not looked at the design of WWD warning messages. Therefore, Finley et al. (2014) used the focus group discussion method to obtain motorists' opinions regarding the design of WWD warning messages for DMSs. Researchers also reviewed previous DMS message design

literature and manuals to gain insight into the design of WWD warning messages. Based on the findings, researchers suggested the single-phase message shown in Figure A-1.

During a WWD event, the location of a wrong-way driver and the lanes affected can be difficult to verify and can change rather quickly. In addition, the focus group results showed that motorists understand the dynamic nature of the situation and difficulty with providing this type of information in a timely manner. Texas DOT personnel also noted that even if the operators have the capability to monitor a wrong-way driver via camera, these operators do not always have time to continuously update a DMS message. Instead, the priority is to convey information to law enforcement so they can apprehend the wrong-way driver. Therefore, researchers did not include location information in the suggested message.

The focus group results also showed that WRONG WAY adequately conveyed the effect on travel (i.e., motorists might encounter a wrong-way driver) and the proper driving action (i.e., motorists should slow down and proceed with caution). In addition, most of the focus group participants did not think drivers should be told to do a specific driving action (e.g., pull over to the shoulder or exit the freeway). Again, due to the dynamic nature of the situation, providing a specific action would be difficult. Thus, researchers also did not include an action statement in the suggested message.

Finley et al. (2014) also suggested that anytime one of these messages is displayed on a DMS, the beacons located on the DMS should be activated. If the DMS does not have beacons, the entire message may be flashed. One line of these messages should never be flashed. The suggested message should be posted on DMSs whenever a wrong-way driver is reported, even if not confirmed, in order to alert motorists to the possibility of a wrong-way driver as soon as possible. When a wrong-way driver is confirmed, there is no need to change the third line of the messages. The message should be displayed along the entire length of the roadway in both directions of travel, and should be displayed until the wrong-way driver is apprehended or the report is canceled.

The Michigan DOT also implemented an initiative to address serious crashes that included low-cost countermeasures to deter wrong-way movements onto freeways (Michigan DOT 2012; Morena and Leix 2012). In 2012, the Michigan DOT began implementing several low-cost safety improvements over a 5-year period at locations where wrong-way maneuvers were more frequently observed (i.e., a partial cloverleaf configuration). These improvements included:

- Lowered height of DO NOT ENTER and WRONG WAY signs,
- Reflective sheeting on the supports of lowered signs,
- Stop lines at exit ramps,
- Wrong-way pavement marking arrows,
- Left-turn pavement marking guides,
- Painted islands between exit and entrance ramps, and
- Increased two-sided delineation along the exit ramp.

WARNING
WRONG WAY DRIVER
REPORTED

Source: Finley et al. 2014.

Figure A-1. Suggested DMS WWD message.

In October 2012, the Illinois Center for Transportation finished a study for the Illinois DOT related to WWD on freeways (Zhou et al. 2012). The research included analysis of wrong-way crashes in Illinois over a 6-year period to determine the contributing factors to wrong-way crashes on freeways and the development of promising, cost-conscious countermeasures to reduce the WWD errors and their associated crashes. Researchers developed a method to rank the high-frequency crash locations based on the number of recorded or estimated wrong-way freeway entries. Interchanges were identified for field reviews, with site-specific and general countermeasures identified for future implementation. Some of the wrong-way countermeasures identified for implementation included:

- Larger DO NOT ENTER and WRONG WAY signs,
- Red reflective sheeting on sign supports,
- WRONG WAY signs with flashing LEDs around the border at high-frequency crash locations, and
- Pavement marking and geometric design enhancements at on-off ramp configurations.

Also in 2012, the Ohio DOT finalized systematic upgrades of DO NOT ENTER, WRONG WAY, and ONE WAY signs to the 2012 *Ohio Manual on Uniform Traffic Control Devices* standards (Ohio DOT 2012). The work was part of an ongoing sign replacement program, which provided for traffic control signs to be replaced regularly to assure adequate nighttime visibility. As part of this effort, Ohio DOT:

- Upgraded signage along freeway and expressway interchanges to enhance the visibility of signage for wrong-way drivers,
- Installed supplemental WRONG WAY signs at 3-ft mounting heights on the non-cloverleaf exit ramps, and
- Installed dual directional route marker assemblies at the ramp ends and pavement marking arrows for positive guidance on the entrance ramps for interchanges where the entrance and exit ramps are side by side.

In 2013, the New York State Thruway Authority installed an ITS-based warning system at one exit along I-190 in

Buffalo (American Traffic Safety Services Association 2014). The system used Doppler radar detection and a small DMS that activated after a wrong-way vehicle was detected. The initial installation displayed the following sequence of messages to a wrong-way driver via the DMS: WRONG WAY, STOP, and PULL OVER. The system was also designed to send alerts to the TMC, police, and other DMSs along the main lanes. The cost of the system was $10,000 per sign, inclusive of development and testing.

Also in 2013, the first National Wrong-Way Driving Summit was held in Illinois. Approximately 130 people from 23 states attended the summit. These individuals represented NTSB, FHWA, American Traffic Safety Services Association, state departments of transportation, enforcement, tollway authorities, universities, and consulting firms. Based on the results of a survey distributed to the attendees, group discussion, and presentations, researchers summarized the various WWD countermeasures implemented by different agencies (see Zhou and Rouholamin 2014b; Zhou and Pour-Rouholamin 2015; Pour-Rouholamin et al. 2014). Signing countermeasures included lowering sign height, using oversized signs, mounting multiple signs on the same pole, applying red retroreflective strips to sign posts, and using FREEWAY ENTRANCE signs. Pavement marking countermeasures included stop lines, wrong-way arrows, lane-use arrows, red retroreflective raised pavement markers (RRPMs), and short-dashed lane delineation through turns. ITS technologies implemented included LED border-illuminated signs, use of DMS to warn right-way drivers, and use of global positioning system (GPS) navigation technologies to provide wrong-way movement alerts. Other countermeasures included entrance/exit ramp separation, raised curb medians, longitudinal channelizers, and changing ramp geometrics.

With respect to the survey, 16 states responded, including states that had already implemented and tested various WWD countermeasures and those planning to address WWD in the future. Half of the survey participants had recently conducted WWD studies in their jurisdictions, and many more were planning to begin their evaluations soon. In addition, one-third of the agencies were using ITS technologies to detect wrong-way drivers and alert the wrong-way driver and/or right-way drivers.

The survey findings showed that all of the entities use WRONG WAY signs on exit ramps and all but two entities install DO NOT ENTER signs on exit ramps. The use of these signs on frontage roads is not as consistent (about 70 percent for DO NOT ENTER signs and 56 percent for WRONG WAY signs). On divided highways, 81 percent of the participants use DO NOT ENTER signs and 75 percent use WRONG WAY signs.

Most of the participants (85 percent) use identical signs on both sides of the roadway and increase the size of the signs (77 percent). In addition, most of the respondents (81 percent) install DO NOT ENTER and WRONG WAY signs at the standard height. Nearly half of the entities surveyed have lowered the height of these signs in special conditions. About 40 percent of the entities surveyed install various combinations of WRONG WAY and DO NOT ENTER signs on the same sign post assembly. Sixty-two percent of the participants add a strip of retroreflective material to the sign post. The survey also found that 63 percent of the respondents face these signs perpendicular to the roadway instead of orienting them toward the target user.

Roughly 70 percent of the participants use the wrong-way arrow, and most of these entities place the arrow on the exit ramp near the intersection with the cross street (71 percent) and at the middle of the exit ramp (64 percent). In some cases, the wrong-way arrow is also located on the exit ramp near the gore area off the main lanes (21 percent) and on the main lane (7 percent). In addition, more than half of the states use red RRPMs to supplement or replace the wrong-way arrow.

The NTSB (2012) special investigation report aimed to identify relevant safety recommendations to prevent wrong-way collisions on highways and access ramps on a national level. As discussed previously, the report characterized WWD in the United States and summarized nine NTSB wrong-way collision investigations. In addition, the report made the following suggestions to address wrong-way collisions:

- Installation of alcohol ignition interlocks on the vehicles of all driving-while-intoxicated offenders,
- Widespread implementation of new in-vehicle alcohol detection technologies in U.S. vehicles,
- Use of traffic control devices to make exit ramps more distinguishable from entrance ramps,
- Use of wrong-way monitoring programs to identify wrong-way drivers,
- Use of navigation system alerts in the vehicle to inform drivers that they have performed a wrong-way movement,
- Development of an assessment tool that states can use to select appropriate countermeasures, and
- Development of a best practices guide for law enforcement on how to respond to a wrong-way driver.

Since alcohol has been found to be the primary contributing factor in many wrong-way crash studies, Finley et al. (2014) investigated the behaviors of alcohol-impaired drivers through two nighttime closed-course studies. While data in response to a simulated environment cannot be directly compared to data collected on an actual road, closed-course study data can be used to compare the relative differences in performance between the various treatments evaluated. The studies were designed to:

- Determine where alcohol-impaired drivers look in the forward driving scene,

- Provide insight into how alcohol-impaired drivers recognize and read signs, and
- Assess the conspicuity of select WWD countermeasures from the perspective of alcohol-impaired drivers.

Finley et al. (2014) found that alcohol-impaired drivers tend to look less to the left and right and more toward the pavement area in front of the vehicle. In addition, researchers confirmed that alcohol-impaired drivers do not actively search the forward driving scene as much as non-impaired drivers. Instead, alcohol-impaired drivers concentrate their glances in a smaller area within the forward driving scene.

Finley et al. (2014) also confirmed that drivers at higher BAC levels took longer to locate signs and must be closer to a sign before they can identify the background color and read the legend. In addition, alcohol-impaired drivers have to be closer to signs with flashing red LEDs around the border before they can read the legend compared to signs without flashing LEDs. Researchers also found that as the BAC level increased, more drivers misidentified the red sign background color, with most thinking that a red sign was an orange sign.

Lowering the height of the white-on-red signs studied did not improve the ability of alcohol-impaired drivers to locate signs, identify the background color, or read the legend compared to the standard sign height (7 ft). Making the sign larger (i.e., oversized), adding red retroreflective sheeting to the sign support, or adding flashing red LEDs around the border of the sign also did not improve the ability of the alcohol-impaired drivers to locate WRONG WAY signs. However, the participants felt that these three countermeasures made it easier to find the WRONG WAY sign. The participants also thought that these three countermeasures caught their attention more than the lowered WRONG WAY sign and the normal size WRONG WAY signs without a conspicuity element.

In an effort to reduce the occurrence of missing RRPMs, Finley et al. (2014) modified the design of the current RRPM wrong-way arrow that Texas DOT uses. Researchers did not find a significant difference in the recognition time between the two wrong-way arrow marking designs. In addition, the participants similarly assessed the ease with which they could find the arrow among the other markings. Thus, it appeared that the modified design performed as well as the current design. Researchers also found that at higher BAC levels, the participants took longer to locate the wrong-way arrow pavement markings, independent of the design, among the other markings.

Overall, Finley et al. (2014) concluded that a wide variety of countermeasures and mitigation methods are needed to combat WWD on freeways. However, based on the findings of this research and anecdotal evidence, Finley et al. suspect that highly intoxicated drivers will not be attracted to or understand most traditional countermeasures and possibly even some innovative dynamic countermeasures. Therefore, Finley et al. also concluded that WWD detection systems are needed. Detection systems can be used to detect wrong-way drivers as they enter the freeway and/or on the main lanes. In addition, detection systems provide data regarding actual wrong-way driver entry points, a critical piece of information that is needed to help practitioners further combat WWD. Detection systems, in conjunction with cameras, can also provide data about wrong-way drivers that self-correct before reaching the main lanes. These data would help practitioners further assess the effectiveness of implemented countermeasures. Finley et al. compiled a catalog of known WWD countermeasures and mitigation methods being used or under research in the United States. Furthermore, Finley et al. developed guidelines for Texas DOT districts to follow to assess the WWD issue and implement countermeasures. These guidelines are shown in Figure A-2.

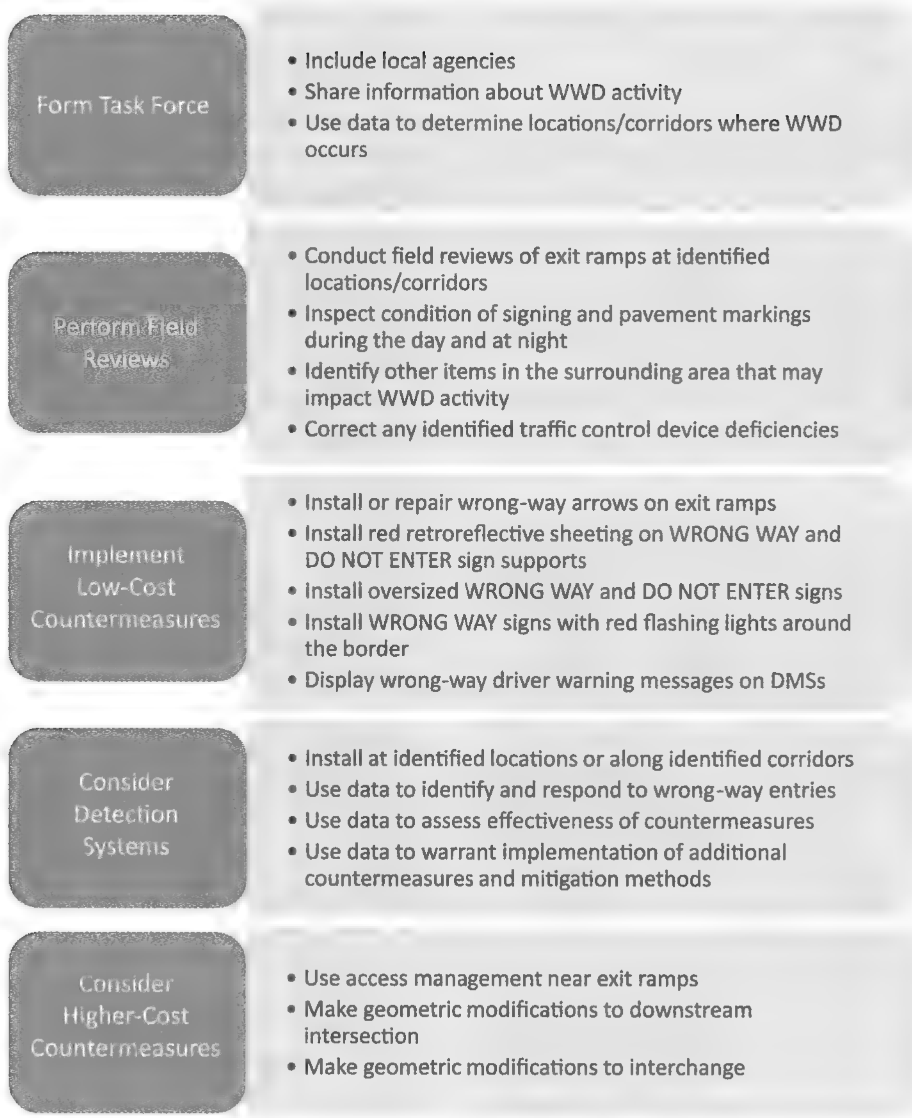
In 2014, Zhou and Rouholamin (2014a) also developed guidelines for reducing wrong-way crashes on freeways. Their document also contains guidance regarding geometric design elements in general and for some specific interchange designs, as well as information regarding enforcement and education.

The *Handbook for Designing Roadways for the Aging Population* (Brewer et al. 2014) recommends:

- The use of larger-than-minimum-size DO NOT ENTER and WRONG WAY signs to increase the letter size,
- The use of retroreflective fluorescent red sheeting material to increase sign conspicuity and legibility for aging drivers,
- The placement of DO NOT ENTER and WRONG WAY signs on both sides of the road,
- The lowering of sign height to 36 inches above the pavement to maximize brightness under low-beam headlights, where all other engineering options have been tried or considered,
- The application of wrong-way arrow pavement markings near the terminus of all exit ramps, and
- The use of red/white bidirectional RRPMs to supplement wrong-way arrow pavement markings where engineering judgment indicates a need for increased conspicuity.

The American Traffic Safety Services Association (2014) has also published a document that contains various case studies regarding emerging WWD countermeasures and a wrong-way driving road safety audit prompt list developed by FHWA. Most of the case studies included in this document have already been discussed, so a simple list of the countermeasures is provided below.

- Low-mounted DO NOT ENTER and WRONG WAY signs,
- LED border-illuminated WRONG WAY signs,



Source: Finley et al. 2014.

Figure A-2. Guideline recommendations for Texas DOT districts.

- Red reflective strips on DO NOT ENTER and WRONG WAY sign posts,
- Red RRPMs,
- Access management,
- ITS detection systems,
- Oversized DO NOT ENTER and WRONG WAY signs, and
- Enhanced pavement markings.

In 2016, the ENTERPRISE Pooled Fund Study published a report that summarized the current practice of wrong-way countermeasures on freeways, including those that use ITSs (Athey Creek Consultants 2016). This report includes details on wrong-way countermeasures used by 13 agencies, as well as evaluation plans, lessons learned, and standards/policies. Many of the countermeasures included in this report have already been described; thus, details are not provided herein. Some additional countermeasures include using dual directional route marker sign assemblies at exit ramps (Ohio) and replacing traditional green ball signal indications with green straight arrow indications (Rhode Island). Researchers concluded that determining the effectiveness of wrong-way countermeasures is challenging due to the random nature of wrong-way crashes, lack of data before the countermeasures were implemented, inconsistency in countermeasure deployment, simultaneous installation of multiple countermeasures, and lack of agency resources.

More recently, Ponnaluri (2016) presented the Florida DOT's policy-oriented framework toward addressing

WWD in a systematic manner. Florida DOT's method included:

- Implementing pilot projects,
- Conducting a statewide study with crash evaluation and field reviews,
- Evaluating and deploying experimental devices,
- Conceptualizing a human factors study,
- Transforming recommendations to design guidance,
- Discussing with planners the interchange types susceptible to WWD,
- Retrofitting exit ramps with the recommended countermeasures, and
- Leveraging the media to promote awareness and to educate the public.

As part of this process, Florida's Turnpike Enterprise (FTE) began a pilot effort on an 18-mi section of the Homestead Extension. In Phase 1, the DO NOT ENTER, WRONG WAY, ONE WAY, NO LEFT/U-TURNS, and KEEP RIGHT signs were replaced with their respective oversized signs. Wrong-way arrows were also added along exit ramps. In Phase 2, FTE implemented vehicle-alerting technology on the main lanes. In Phase 3, FTE installed LED border-illuminated WRONG WAY signs with vehicle detection and enhanced Florida DOT SunGuide® software. Florida DOT District 3 also installed additional signs and pavement markings, as well as vehicle-activated blank-out WRONG WAY signs at four interchanges along Interstate 10. Large WRONG WAY signs were also installed on existing overhead guide sign trusses over the main lanes, and interstate pavement shields with straight arrows were added on the arterial turn lanes. Similar to NTTA, Florida DOT also decided to replace left-turn pavement markings, when they precede the turn lanes, with a combination of interstate pavement shield, cardinal direction, and straight arrows. While these efforts did not include a post-deployment evaluation, Florida DOT and FTE offices are closely monitoring citizen response, media interest, and law enforcement input. Ponnaluri concluded that no one sign, pavement marking, or technology by itself can alert a driver to a potential wrong-way maneuver, but their combined effect seems to be effective.

The Florida DOT Traffic Engineering and Research Laboratory also received permission from FHWA to experiment with red rapid rectangular flashing beacons (RRFBs) and a three-row pattern of in-pavement red internally illuminated RPMs placed along exit ramps. Studies to assess the effectiveness of these emerging countermeasures are currently underway. Florida DOT is also currently sponsoring a statewide WWD study to understand the reasons why drivers enter freeways going the wrong direction.

The Central Florida Expressway Authority (CFX) has also assessed the extent of wrong-way crashes on CFX tollways. Based on the findings, the University of Central Florida investigated and tested potential WWD countermeasures and developed a field inspection checklist for inspectors to use to ensure that the standard signs and pavement markings were installed and properly maintained (Al-Deek et al. 2015). After receiving permission to experiment from FHWA in October 2014, CFX installed red rectangular flashing beacons (RFBs) above and below WRONG WAY signs at five ramps (one on SR 520 and four on SR 408). In addition, CFX installed two cameras (one forward-facing and one side facing) and two radar sensors (one forward-facing and one rear facing) at each of these ramps. When a wrong-way vehicle is detected, the RFBs will flash in a wig-wag pattern to warn the driver, and an alert will be sent to the nearby TMC.

In 2015, TTI and the Southwest Research Institute began working with Texas DOT to develop CV applications that would detect wrong-way vehicles, notify traffic management agencies and law enforcement, and alert affected travelers. In Phase I, the research team reviewed the state of the practice regarding ITS and CV technologies being applied as wrong-way driving countermeasures. The research team then identified user needs associated with the implementation of a CV wrong-way driving system, assessed motorist understanding of wrong-way driver warning messages posted on dynamic message signs, and ascertained preliminary ways to connect with law enforcement. Phase I culminated in the development of a concept of operations, functional requirements, and high-level system design for a CV test bed for wrong-way driving applications (Finley et al. 2016a).

In Phase II, the research team developed a proof-of-concept CV wrong-way driving detection and management system at a closed-course facility. The purpose of the test bed was to provide an off-roadway location to test and fine-tune the system components and operations prior to installing them on an actual roadway. As part of the prototype development, the research team generated a detailed system design based on requirements that were established in Phase I. The research team then procured the hardware components needed to build the prototype system. Furthermore, the research team developed detailed system architecture, integrated hardware and software components, performed validation testing, and conducted a demonstration of the system. In Phase II, the research team also conducted human factors studies to investigate the in-vehicle information needs of right-way drivers when a wrong-way driving event occurs. Researchers conducted a formal task analysis to identify critical stages where right-way drivers could make a better decision if information was provided to them through connected vehicle technology. Researchers then used structured interviews and surveys to identify the information needs of right-way drivers and evaluate comprehension and preference of message wording and timing (Finley et al. 2017).

Summary

The research team reviewed previous domestic and international research to identify the characteristics of wrong-way crashes and summarize the use of traffic control devices and ITS technologies to deter wrong-way movements on freeways and divided highways. Overall, to date, most of the WWD research has focused on freeways; thus, very little is known about the characteristics of wrong-way crashes and effectiveness of countermeasures on divided highways. The key findings regarding wrong-way crashes were:

- Wrong-way crashes on freeways and divided highways tend to be more severe (i.e., a greater proportion resulting in a fatality or serious injury than other types of crashes),
- Wrong-way crashes on freeways tend to occur more frequently in urban areas, at night, and on the weekend,
- The primary origin of wrong-way movements on freeways is entering an exit ramp,
- Most wrong-way crashes on freeways occur in the lane closest to the median,
- The primary origin of wrong-way movements on divided highways is at intersections with median openings,
- Wrong-way drivers tend to be young males,
- Driving under the influence of alcohol and/or drugs is the primary contributing factor in most of the wrong-way crashes, and
- Elderly drivers are overrepresented in wrong-way collisions.

Other contributing factors include interchange design, inclement weather, driver inattention, driver confusion, physical or mental illness, insufficient lighting, and insufficient sight distance. Wrong-way maneuvers also occur because of intentional driver behaviors, such as driving backward, making U-turns, and attempting suicide.

Many traffic control devices and ITS technologies have been developed and tested since the 1960s. However, similar to the crash data analyses, most implementations and evaluations have occurred on freeways. Table A-1 contains a summary of the traffic control devices and associated ITS/technology systems documented in previous research.

Table A-1. Summary of traffic control device and ITS/technology wrong-way driving countermeasures.

Preventive	ITS/Technology
Traditional signs	Detects wrong-way driver
• DO NOT ENTER	• Sensors
• WRONG WAY	• Cameras
• ONE WAY	Warns wrong-way driver
• Divided highway crossing	• Active signs
• Movement prohibition	• Pavement markings
• Freeway entrance	• In-vehicle (emerging approach)
• KEEP RIGHT	Notifies TMC and law enforcement
• Directional route marker assembly	Verifies and/or monitors event
Enhanced static signs	• Sensors
• Additional signs (mounted separately or on the same sign post)	• Cameras • TMC operator
• Oversized signs	• GPS
• Lower mounting height	Warns right-way drivers
• Red retroreflective tape on sign post	• DMS
Active signs	• In-vehicle (emerging approach)
• Blank-out	
• Beacons	
• LEDs around sign border	
• RRFBs/RFBs (experimental)	
Pavement markings	
• Wrong-way arrows	
• Lane-use arrows	
• Stop lines	
• Lane line extensions for turning movements	
• Route designation shields	
Active pavement markings	
• In-pavement lighting (experimental)	
Other traffic control devices	
• Red delineators along exit ramp	
• Green straight arrow signal indications	

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APPENDIX B

MUTCD Review

Introduction

The *2009 Manual on Uniform Traffic Control Devices with Revision Numbers 1 and 2* (FHWA 2012) contains information regarding the installation of DO NOT ENTER, WRONG WAY, ONE WAY, and other regulatory signs, as well as pavement markings, to deter wrong-way movements at intersections on divided highways and at exit ramps on freeways. However, inconsistencies between the 2009 *Manual on Uniform Traffic Control Devices* (MUTCD), other manuals, and state practice have been identified. In order to gain a better understanding of these issues and the MUTCD sections applicable to this research effort, the research team reviewed the 2009 MUTCD and identified material that may need to be revised based on this project's research findings. The research team then reviewed past MUTCDs and National Committee on Uniform Traffic Control Devices (NCUTCD) meeting documentation to gain a historical perspective of the current guidelines. The research team also reviewed current and past editions of the Uniform Vehicle Code (UVC) and the AASHTO *Policy on Geometric Design of Highways and Streets* (also known as the Green Book).

MUTCD Language Review

Definitions

According to Section 1A.13 in the 2009 MUTCD, the median is "the area between two roadways of a divided highway measured from edge of traveled way to edge of traveled way" (FHWA 2012). The traveled way is defined as "the portion of the roadway for the movement of vehicles, exclusive of shoulders, berms, sidewalks, and parking lanes" (FHWA 2012). In addition, the median definition states that "the median excludes turn lanes," and that "the median width might be different between intersections, interchanges, and at opposite approaches of the same intersection" (FHWA 2012). Figure B-1 contains MUTCD Figure 2B-15, which shows how the median width is measured. The first formal definition of median was incorporated into the 1961 MUTCD (Bureau of Public Roads 1961), but it did not include a description of how to measure the median width. The current definitions for median and traveled way were first introduced in the 2000 MUTCD (FHWA 2001).

Similarly, the Green Book (AASHTO 2011) defines the median width as the distance between the edges of the traveled way in opposing directions, including the width of the left shoulders. In addition, the traveled way is defined such that it excludes shoulder and bicycle lanes. While not explicitly stated, both National Cooperative Highway Research Program (NCHRP) Report 375 (Harwood et al. 1995) and NCHRP Report 650 (Maze et al. 2010) researchers interpreted the Green Book median width definition to include median turn lanes. The research team believes that this interpretation is based on several other statements and figures regarding the median and median width measurement in the Green Book. One of the principal functions of medians listed in the Green Book is to provide space for speed changes and storage of vehicles turning left or making U-turns. Furthermore, several figures in the Green Book show the median left-turn lane included in the median width measurement.

Considering human factors, it is logical to assume that median width (however measured) would be a pertinent factor in wrong-way movement crashes on divided highways. As the median width increases, the ability of drivers to determine whether the intersecting roadway is divided or undivided becomes more difficult, especially at night. Thus, wider medians may increase the potential for driver error that leads to a wrong-way movement. This notion is supported by the Green Book, which states that when drivers on the intersecting roadway cannot readily see the far side of the divided highway, it may hinder their ability to recognize the roadway is divided. When wider medians are used, the Green Book recommends that signing and visual cues be provided to discourage wrong-way movements.

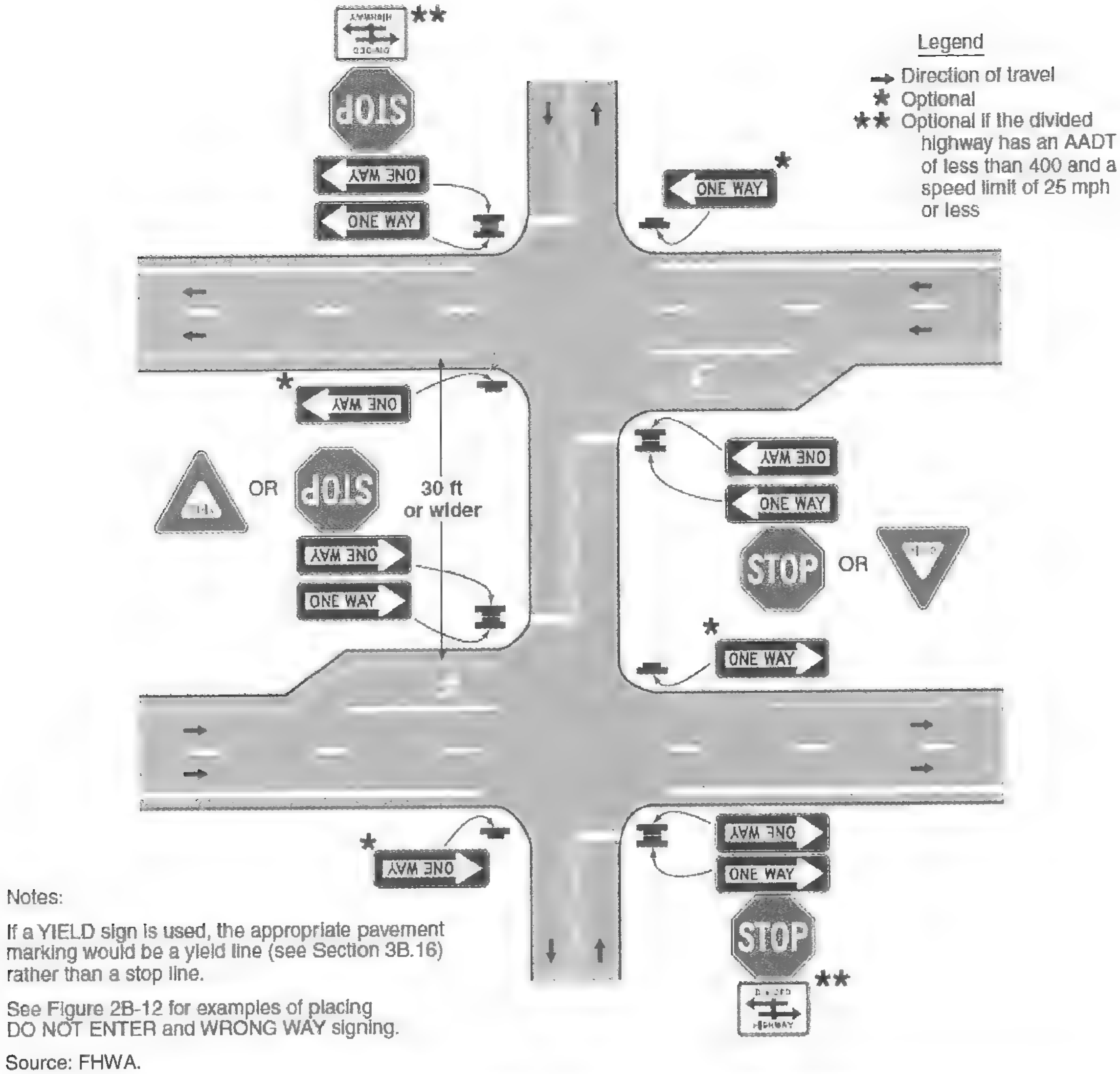


Figure B-1. MUTCD Figure 2B-15: ONE WAY signing for divided highways with median widths of 30 feet or wider.

In the 2009 MUTCD, the selection of proper wrong-way traffic control at divided highway intersections depends on whether the crossing is considered a single intersection or two separate intersections. Currently, median width is the only criterion used to make this decision. The definition of intersection in Section 1A.13 of the 2009 MUTCD states that when two roadways are 30 ft or more apart, each crossing must be considered a separate intersection. Section 2A.23 of the 2009 MUTCD further indicates that the median width used to determine the number of intersections at a divided highway crossing should be measured at the median opening. A review of the MUTCD's history shows that the 30-ft median width threshold first appeared in the 1948 MUTCD (Public Roads Administration 1948). Furthermore, the intersection definition in the 1948 MUTCD appears to be identical to the intersection definition in the 1944 UVC (Public Roads Administration 1945). According to the NCHRP 375 Report, it is generally believed that the 30-ft median width threshold was based on state agency practice at the time.

The Green Book indicates that most median widths range from 4 to 80 ft. Furthermore, the Green Book states that median widths less than 25 ft wide should be avoided because drivers may stop in the median with part of their vehicle unprotected from through traffic. Wider medians may be needed at these intersections for school buses and large tractor-trailer trucks (50 ft and 80 ft, respectively). These statements led NCHRP Report 650 researchers to conclude that if the 30-ft MUTCD median width threshold was based on vehicle storage requirements, it did not agree with the Green Book. Furthermore, the authors of *NCHRP Report 650* recommended that the basis for the MUTCD 30-ft median width threshold be explained.

More recently, Khazraee and Hawkins (2015) examined the fundamental issues associated with the function of treating a divided highway crossing as one or two intersections. These researchers determined that the main shortcoming of the MUTCD criterion relates to the definition and measurement of the median width at the intersection, as well as the lack of consideration of the interaction of opposing left turns in the median and the median opening length. These researchers recommended that the median width be redefined as the distance from the inside of the left-turn lane in one direction to the inside of the left-turn lane in the opposing direction. Therefore, the median width would not vary on opposite approaches of the same intersection.

Using this modified definition of the median width and accounting for the median opening length, Khazraee and Hawkins (2015) used the Green Book minimum turning paths to develop a set of minimum requirements for controlling divided highway crossings as one or two intersections. The results showed that, in most cases, the 30-ft median width threshold was not adequate as the sole criterion and usually underestimated the actual requirements for operation as two separate intersections. The researchers suggested that the 30-ft threshold be removed and replaced with a figure that provides guidance on the appropriate control at a divided highway intersection based on the modified median width and median opening length. Essentially, this guidance treats a divided highway crossing as a single intersection only if the geometry provides for simultaneous opposing left turns (i.e., in front of each other). The crossing is considered to be two separate intersections only if the geometry provides for interlocking opposing left turns (i.e., behind one another). The researchers also suggested that the MUTCD criteria include guidance about site-specific conditions, such as area type (e.g., urban or rural).

The lack of a consistent median width definition makes it difficult for practitioners to uniformly use and apply the standards and guidance found in the MUTCD and Green Book. In addition, questions have been raised as to the appropriateness of the median width threshold used in the MUTCD to determine whether a crossing at a divided roadway is considered a single intersection or two separate intersections.

Wrong-Way Traffic Control at Divided Highways

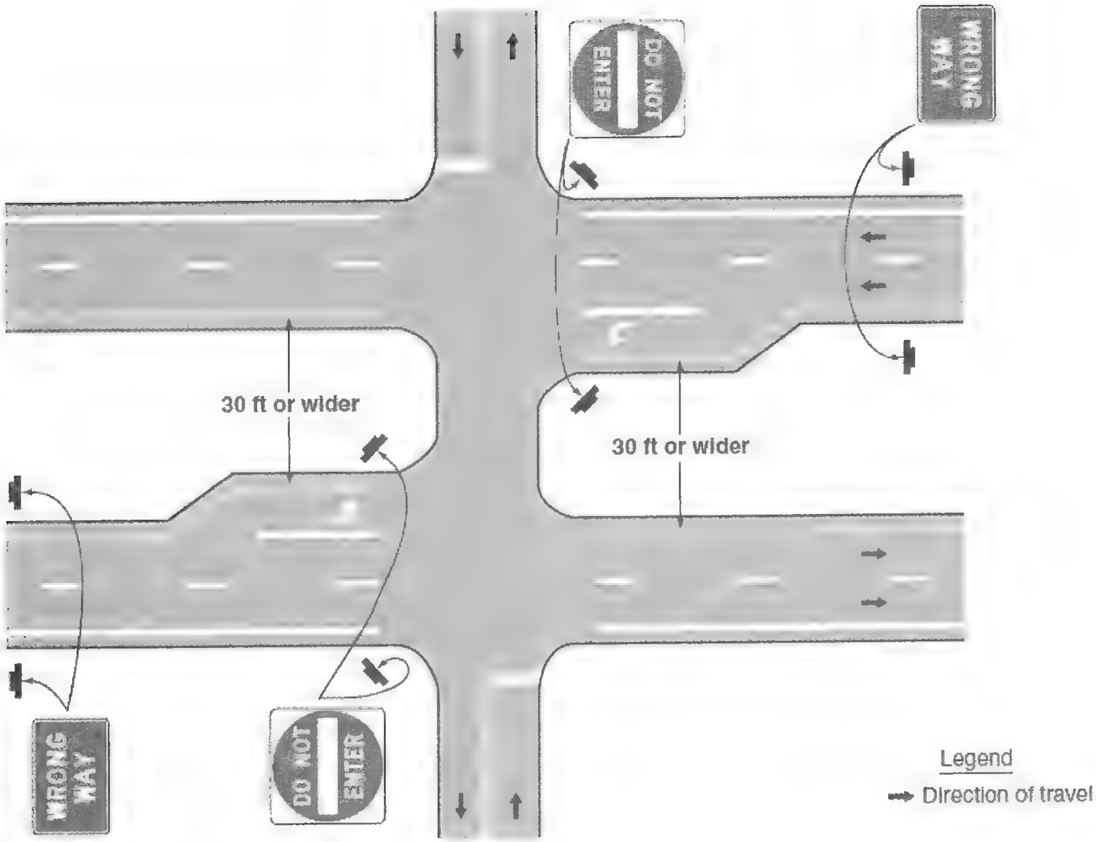
As indicated previously, selection of proper wrong-way traffic control at divided highway intersections depends on whether the median width is greater than or equal to 30 ft or less than 30 ft. Several figures in Section 2B of the 2009 MUTCD show the signing at crossings on divided highways based on the 30-ft median width threshold. Various versions of these figures have existed in the MUTCD since the 1978 edition.

For median widths 30 ft or wider, the interior approaches in the median should be controlled with STOP or YIELD signs (see Figure B-1). Divided highway crossing signs are required on unsignalized minor street approaches when both left and right turns are permitted on a divided highway unless the divided highway has an average annual daily traffic less than 400 and a speed limit of 25 mph or less. These required signs are to be located on the right-hand side of each minor street approach and mounted beneath a STOP or YIELD sign or on a separate support. Optional divided highway crossing signs can be installed on the left-hand side of each minor street approach (although these optional signs are not shown in MUTCD Figure 2B-15; see Figure B-1). The divided highway crossing sign is intended to advise minor street users that they are approaching an intersection with a divided highway. ONE WAY signs are also required on the near right and far left corners of each intersection. Additional ONE WAY signs may be added on the far right corners of each intersection.

Figure 2B-12 in the 2009 MUTCD (see Figure B-2) shows the location of DO NOT ENTER and WRONG WAY signs for median widths 30 ft or wider. However, this figure does not depict which signs are required and which signs are optional. The text in Section 2B.37 of the 2009 MUTCD states that the DO NOT ENTER sign should be mounted on the right-hand side of the road directly in view of road users that might wrongly enter a divided highway. A second DO NOT ENTER sign can be installed on the left-hand side of the road, especially when traffic approaches from an intersecting roadway. However, since the required and optional signs are not shown in the figure, the determination of the left-hand and right-hand side of the road is ambiguous (i.e., are the sign locations in reference to the correct direction of travel or the wrong direction of travel?).

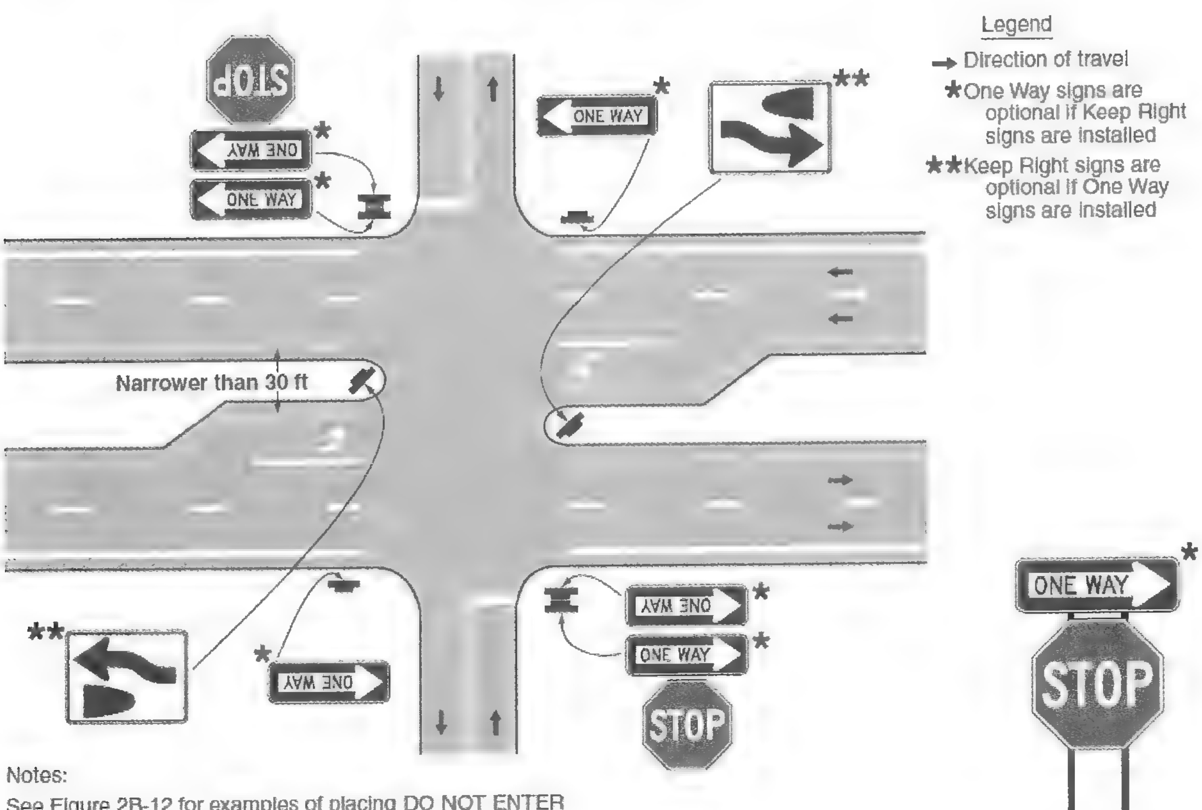
The text in Section 2B.38 of the 2009 MUTCD indicates that WRONG WAY signs may be used to supplement DO NOT ENTER signs. While the 2009 MUTCD states that WRONG WAY signs should be placed farther from the crossroad than DO NOT ENTER signs, it too does not indicate on which side of the road. The research team believes that since WRONG WAY signs supplement DO NOT ENTER signs, it is implied that both signs would be located on the same side of the road. However, language should be added to clarify the location of WRONG WAY signs relative to DO NOT ENTER signs. In addition, an optional designation should be noted adjacent to all WRONG WAY signs in MUTCD Figure 2B-12.

For median widths less than 30 ft, the 2009 MUTCD contains a figure for conventional left-turn lanes (see Figure B-3) and separated (offset) left-turn lanes (see Figure B-4). In both cases, there is no control on the interior approaches. However, either KEEP RIGHT or ONE WAY signs are required.



Source: FHWA.

Figure B-2. MUTCD Figure 2B-12: locations of wrong-way signing for divided highways with median widths of 30 feet or wider.



Notes:

See Figure 2B-12 for examples of placing DO NOT ENTER and WRONG WAY signing.

See Figure 2B-15 if median is 30 feet or more in width.

Source: FHWA.

Figure B-3. MUTCD Figure 2B-16: ONE WAY signing for divided highways with median widths narrower than 30 feet.

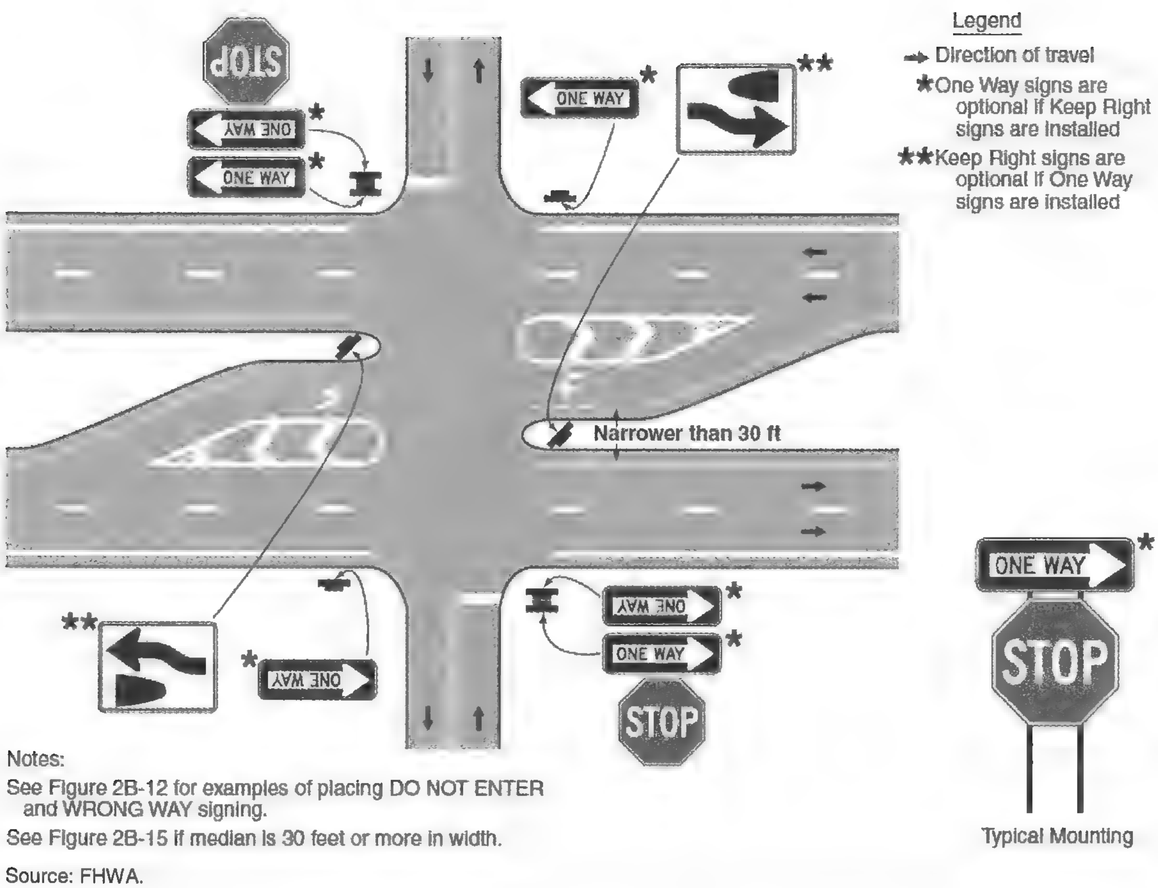


Figure B-4. MUTCD Figure 2B-17: ONE WAY signing for divided highways with median widths narrower than 30 feet and separated left-turn lanes.

Section 2B.40 notes that if KEEP RIGHT signs are used, they should be placed as close as possible to the ends of the median and should be visible to traffic on the divided highway and the crossroad. If ONE WAY signs are used, they must be placed on the near right and far left corners of the intersection and be visible to each crossroad approach. Additional ONE WAY signs may be added on the far right corners of the intersection. However, the MUTCD figures do not distinguish between required and optional ONE WAY signs when KEEP RIGHT signs are not installed. In addition to signage, lane-use arrows should also be placed near the downstream end of the offset left-turn lanes. Interestingly, both MUTCD figures for median widths less than 30 ft reference MUTCD Figure 2B-12 (see Figure B-2) for the placement of DO NOT ENTER and WRONG WAY signing, even though this figure is for medians 30 ft or wider. Language referencing the application of KEEP RIGHT signs for deterring wrong-way movements at divided highway crossings should be added to Section 2B.32 (KEEP RIGHT and KEEP LEFT signs).

A survey of highway agencies documented in *NCHRP Report 375* (Harwood et al. 1995) found that in the 1990s, current practice was to use no traffic control in the median where the median width was less than 30-ft wide (i.e., treated as one intersection). At medians more than 85-ft wide, agencies consistently treated the two roadway crossings as separate intersections and controlled the interior approaches in the median with STOP signs. However, the types of control used at intersections where the median width ranged from 30 to 85 ft consisted of STOP signs, YIELD signs, or no control for the interior approaches in the median. This variation in control demonstrated that median widths greater than or equal to 30 ft are not always signed as two intersections. It should be noted that for *NCHRP Report 375*, the median width included left-turn lanes (if present).

In 2010, *NCHRP Report 650* (Maze et al. 2010) included recommendations for the addition of several figures to illustrate regulatory signing and pavement markings for a variety of conditions, as well as revisions to existing figures, to address identified inconsistencies and insufficiencies. While some of these recommendations were incorporated into the 2009 MUTCD, many issues still remain. In addition, it is unknown whether the figures and/or text need to address other characteristics such as speed (low or high) and setting (urban or rural).

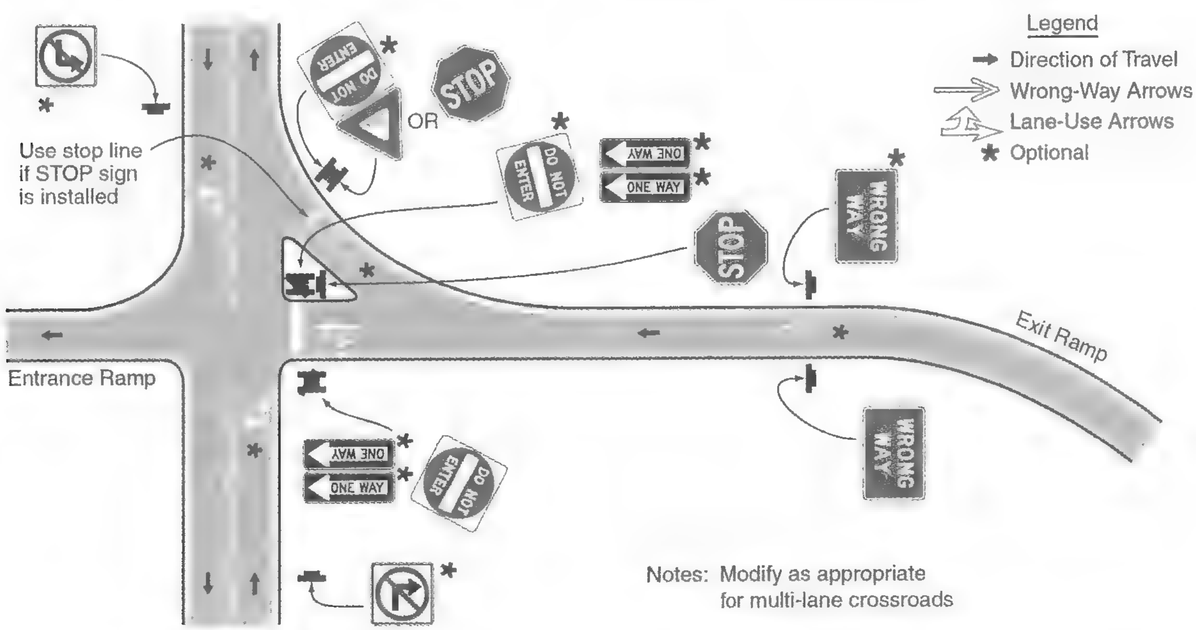
Wrong-Way Traffic Control at Interchange Ramps

The 2009 MUTCD also contains information regarding wrong-way traffic control at interchange ramps in Section 2B.41. This section was first included in the 1978 MUTCD (FHWA 1978) and was located in Chapter 2E until the 2009 MUTCD. Figure B-5 contains MUTCD Figure 2B-18, which shows an example application of regulatory signing and pavement marking at an exit ramp termination to deter wrong-way entry. When an interchange exit ramp intersects a crossroad such that a wrong-way entry could inadvertently be made, the 2009 MUTCD text states that the following signs shall be used:

- At least one ONE WAY sign for each direction of travel on the crossroad. These signs must be placed at the intersection of the exit ramp and the crossroad.
- At least one DO NOT ENTER sign conspicuously placed near the downstream end of the exit ramp in full view of a road user starting to make a wrong-way maneuver from the crossroad.
- At least one WRONG WAY sign on the exit ramp facing a road user traveling in the wrong direction.

Additional ONE WAY, DO NOT ENTER, and WRONG WAY signs may be placed as shown in Figure B-5. However, all of the ONE WAY signs in MUTCD Figure 2B-18 are denoted as being optional, even though the text requires at least one ONE WAY sign in each direction. Furthermore, Figure B-5 shows the optional use of movement prohibition signs (R3-1 and R3-2) on the crossroad approaches to the intersection with the exit ramp. Yet, these signs are not discussed in Section 2B.41. The 2009 MUTCD text also provides the option of using freeway entrance signs (Section 2D.46) to deter wrong-way movements.

The option to lower DO NOT ENTER and/or WRONG WAY signs was first introduced in the 2009 MUTCD, although this technique has been used in California since the 1970s. At locations where there are no parked cars, pedestrian activity, or other obstructions (e.g., snow, vegetation, guardrail) and an engineering study indicates that lowering the mounting height would address wrong-way movements at freeway exit ramps, DO NOT ENTER and/or WRONG WAY signs may be installed at a minimum mounting height of 3 ft. However, some agencies question the use of this minimum mounting height, preferring 2 ft. Based on NCUTCD documentation in 2006, at least three states had adopted the practice of lowering the mounting height of DO NOT ENTER and WRONG WAY signs. Some states used 2 ft, while others utilized 4 ft to accommodate snow removal. The NCUTCD documentation also included an FHWA Resource Center recommendation for a minimum mounting height of 3 ft when all other engineering options have been tried or considered. Recognizing the visibility benefits of the lowered sign height while also acknowledging concerns over their breakaway characteristics, the NCUTCD recommended a minimum mounting height of 3 ft.



Source: FHWA.

Figure B-5. MUTCD Figure 2B-18: example application of regulatory signing and pavement markings at an exit ramp termination to deter wrong-way entry.

In addition to signage, the following pavement markings may be used to deter wrong-way movements at interchange ramps:

- Double solid yellow lines should be used as a centerline for an adequate distance on both sides of the crossroad approaching the intersection with the exit ramp.
- Lane-use arrows in each lane of the exit ramp should be located near the intersection with the crossroad to indicate permissive direction of travel (see Figure B-6). Lane-use arrows may also be used on the crossroad near the intersection.
- Wrong-way arrows may be placed upstream from the ramp terminus and/or near the crossroad intersection to indicate the correct direction of travel. Wrong-way arrows may be pavement markings or bidirectional red-and-white raised pavement markers that show red to wrong-way drivers and white to right-way drivers (see Figure B-6).

Guidance is also provided for interchange entrance ramps. When an entrance ramp merges with a through roadway and the design of the interchange does not make the direction of traffic evident, a ONE WAY sign should be placed on each side of the through roadway near the ramp merge point (see Figure B-7). MUTCD Figure 2B-19 also allows for the optional use of wrong-way arrows and a movement prohibition sign.

Language in Section 2B.41 of the 2009 MUTCD also allows other standard warning or prohibitive methods and devices to be installed to deter wrong-way movement where engineering judgment determines that a special need exists. However, Paragraph 7 refers to the same section in which it is located (2B.41) for more information about wrong-way movements at at-grade intersections on expressways. Previous editions of the MUTCD referenced the WRONG WAY sign section (2B.38).

Summary

In order to gain a better understanding of the current traffic control device standards, guidance, and options related to wrong-way traffic control at divided highway crossings and at exit ramps on freeways, the research team reviewed the 2009 MUTCD. The research team also reviewed past editions of the MUTCD to gain a historical perspective of the current language and compared the current language to other resources to identify potential conflicts. Through this process, the research team identified several issues with existing language and figures. These items are summarized in Table B-1.

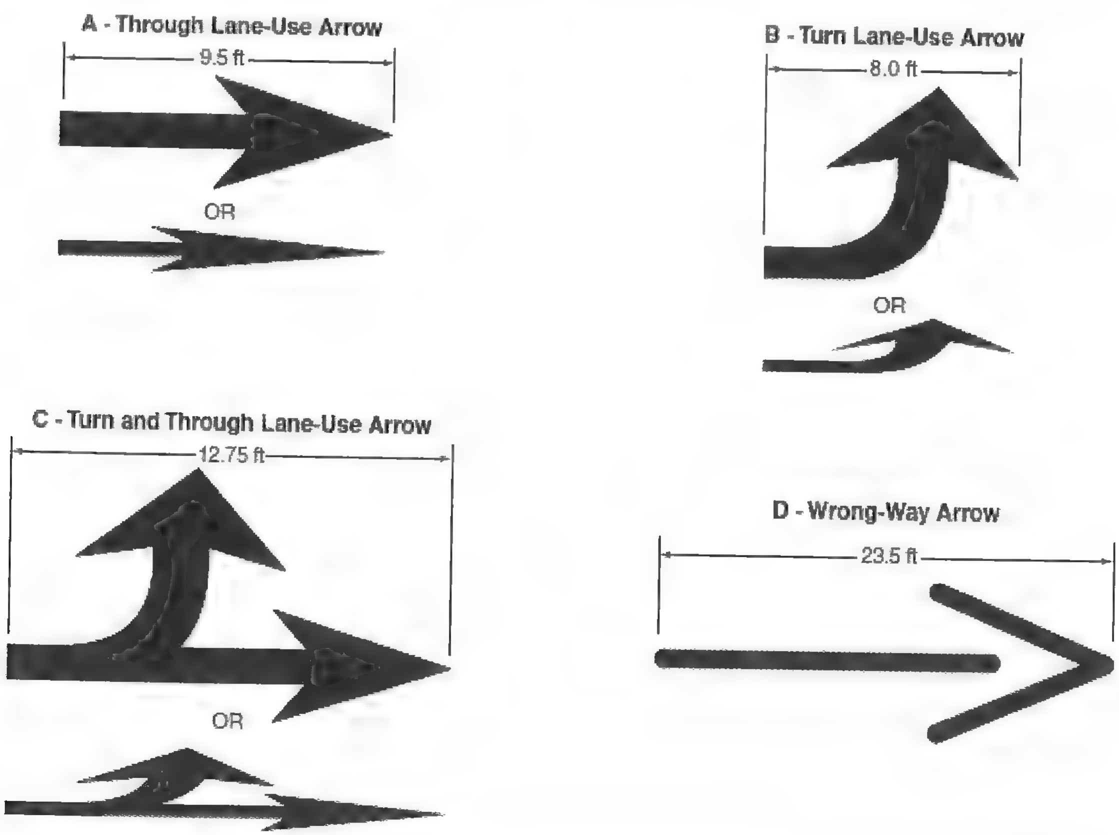
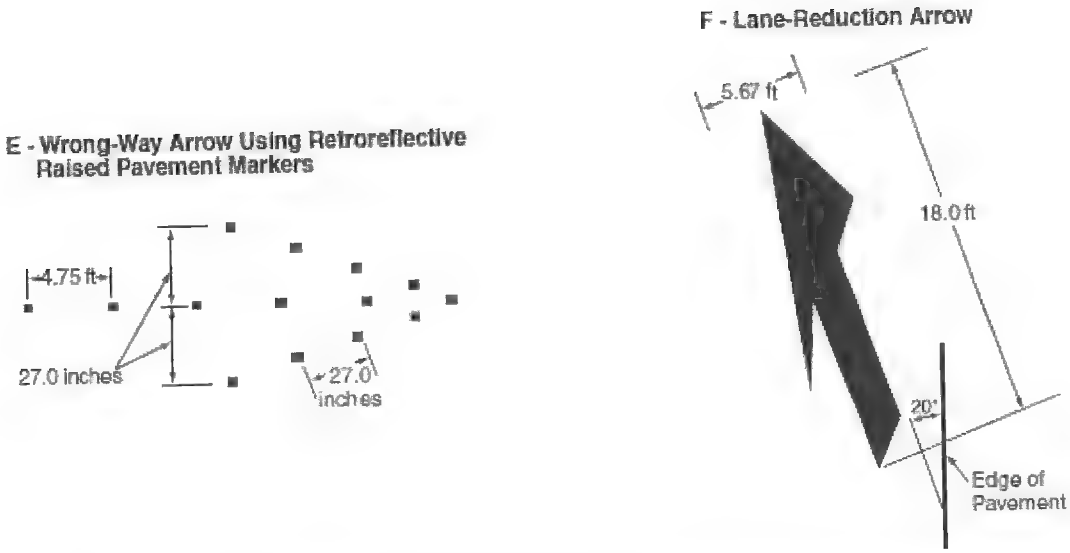


Figure B-6. MUTCD Figure 3B-24: examples of standard arrows for pavement markings.
(continued on next page)

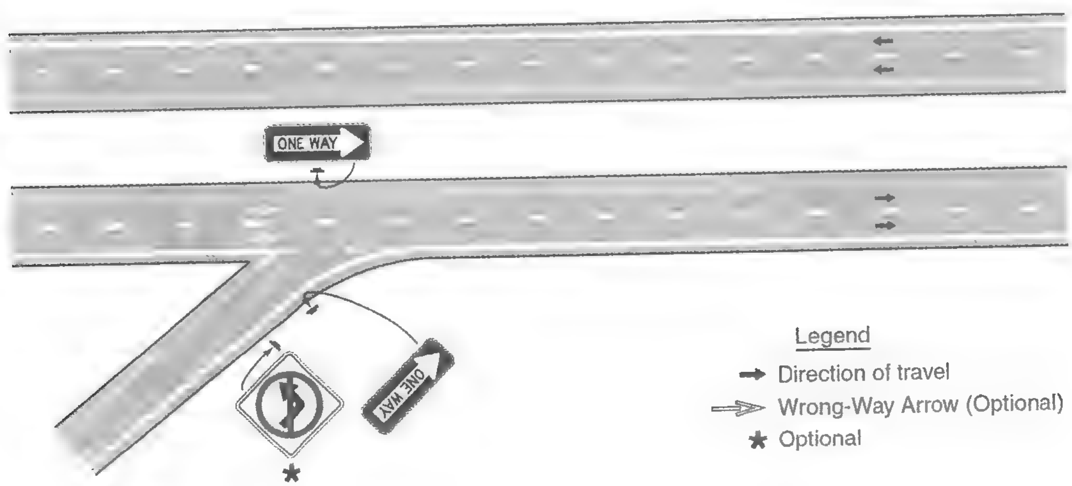


Notes:

1. Typical sizes for normal installation; sizes may be reduced approximately one-third for low-speed urban conditions; larger sizes may be needed for freeways, above average speeds, and other critical locations.
2. The narrow elongated arrow designs shown in Drawings A, B, and C are optional.
3. For proper proportion, see the Pavement Markings chapter of the "Standard Highway Signs and Markings" book (see Section 1A.11).

Source: FHWA.

Figure B-6. (Continued).



Source: FHWA.

Figure B-7. MUTCD Figure 2B-19: example of application of regulatory signing and pavement markings at an entrance ramp terminal where the design does not clearly indicate the direction of flow.

Table B-1. Summary of Issues Identified in the 2009 MUTCD.

2009 MUTCD Section/Figure	Identified Issue
Section 1A.13—Definitions of Headings, Words, and Phrases in the Manual	Lack of a consistent median width definition between the MUTCD and Green Book.
Section 1A.13—Definitions of Headings, Words, and Phrases in the Manual	Appropriateness of the 30-ft threshold median width to determine whether a crossing at a divided highway is considered a single intersection or two separate intersections.
Section 2B.32—Keep Right and Keep Left Signs (R4-7, R4-8)	Need to reference Section 2B.40 for wrong-way applications.
Section 2B.37—DO NOT ENTER Sign (R5-1)	Ambiguity surrounding the side of the road for required and optional signs.
Section 2B.38—WRONG WAY Sign (R5-1a)	Ambiguity surrounding the side of the road for signs.
Figure 2B-12—Locations of Wrong-Way Signing for Divided Highways with Median Widths of 30 Feet or Wider	Does not indicate which DO NOT ENTER and WRONG WAY signs are required and which signs are optional. There is no figure for the location of DO NOT ENTER and WRONG WAY signs for median widths narrower than 30 ft.
Figure 2B-15—ONE WAY Signing for Divided Highways with Median Widths of 30 Feet or Wider	Optional divided highway crossing sign on left-hand side of each minor approach is not shown.
Figure 2B-16—ONE WAY Signing for Divided Highways with Median Widths Narrower Than 30 Feet	The notes reference Figure 2B-12, which is for median widths 30 ft or wider. There is no figure for the location of DO NOT ENTER and WRONG WAY signs for median widths narrower than 30 ft. Legend implies that all ONE WAY signs are required if KEEP RIGHT signs are not used. However, Section 2B.40 indicates that only two of the ONE WAY signs are required and one is optional.
Figure 2B-17—ONE WAY Signing for Divided Highways with Median Widths Narrower Than 30 Feet and Separated Left-Turn Lanes	The notes reference Figure 2B-12, which is for median widths 30 ft or wider. There is no figure for the location of DO NOT ENTER and WRONG WAY signs for median widths narrower than 30 ft. Legend implies that all ONE WAY signs are required if KEEP RIGHT signs are not used. However, Section 2B.40 indicates that only two of the ONE WAY signs are required and one is optional.
Section 2B.41—Wrong-Way Traffic Control at Interchange Ramps	Paragraph 7 refers to the same section in which it is located (2B.41). Previous editions of the MUTCD referenced 2B.38.
Figure 2B-18—Example Application of Regulatory Signing and Pavement Markings at an Exit Ramp Termination to Deter Wrong-Way Entry	All of the ONE WAY signs are noted as optional even though the text in Section 2B.41 requires at least one ONE WAY sign in each direction.
Figure 2B-18—Example Application of Regulatory Signing and Pavement Markings at an Exit Ramp Termination to Deter Wrong-Way Entry	Figure shows optional use of movement prohibition signs, but these signs are not discussed in text in Section 2B.41.

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APPENDIX C

Suggested Revisions to MUTCD

In this appendix, researchers provide an overview of the suggested revisions to the language in the *2009 Manual on Uniform Traffic Control Devices with Revision Numbers 1 and 2*, including their reasoning for the changes. This is followed by the detailed suggestions.

Summary of and Reasons for Suggestions

Revisions Regarding Traffic Control Devices for Wrong-Way Movements

Section 1A.13—Definition for "#94, Intersection"

- The research indicates that the 30-ft threshold criterion may not be appropriate for distinguishing between one or two intersections. However, the focus of this research effort was on wrong-way movements, and there are many other factors that impact the function of a divided highway crossing as one intersection or two.
- Whether a divided highway functions as one or two intersections is determined by whether there is right-of-way control on the interior approaches. Interior right-of-way control is appropriate when two conditions are present: (1) the paths of opposing left turns from the divided roadway cross one another, and (2) there is adequate storage on the interior approach for a vehicle to stop at the stop/yield line. If the opposing left-turn paths from the divided highway do not cross or there is not adequate storage in the interior, then the divided highway crossing functions as a single intersection. Thus, the key to intersection right-of-way control is based on left-turn paths and interior storage. Researchers have revised the definition of intersection in element (c) to represent this. The revision eliminates the 30-ft criterion and allows the engineer to determine the intended function of a divided highway crossing.
- Replacing the existing paragraph (c) in the definition for an intersection with a new paragraph (c) eliminates the need for paragraph (d) in the definition. The new paragraph (c) deletes the reference to the 30-ft separation distance.

Section 1A.13—Definition for "#115, Median"

- The definitions in early editions of the MUTCD duplicated those in the Uniform Vehicle Code (UVC).
- No edition of the UVC (including the three most recent editions: 1987, 1992, and 2000) contain a definition for the term median.
- The 1971 edition included a list of terms and definitions.
- The 1978 and the 1988 editions of the MUTCD removed the terms and definitions since the terms had the definitions as presented in the UVC or the American Association of State Highway and Transportation Officials (AASHTO) highway definitions.
- The written definition for median first appeared in the MUTCD in the 2000 edition. The chair of the National Committee on Uniform Traffic Control Devices (NCUTCD) Edit Committee during the time the 2000 MUTCD was being prepared verbally indicated that the definition for median was developed

by the committee based on judgment. As such, there is no documentation to support the creation of this definition.

- The measurement of the median width was first illustrated in the MUTCD in the 2003 edition.
- The current MUTCD definition for median width conflicts with the definition used in the AASHTO Green Book. The AASHTO Green Book definition preceded the MUTCD definition. The AASHTO definition was used as the basis in prior National Cooperative Highway Research Program research on median intersection design (Harwood et al. 1995).
- Researchers suggested changing the definition and deleting how the median width is measured. Once the 30-ft criterion is removed (see above), the portion of the definition related to measuring width becomes unnecessary. Researchers reviewed the MUTCD for sections that reference median width and suggested changes where needed to accommodate the deletion of this definition.
- Researchers considered including the sentence "The median width defines the available storage distance for the interior of a divided highway" but decided not to include this sentence because it is overly restrictive and the actual storage distance could be as wide as the AASHTO median width definition, although such storage would prevent left turns from the divided highway.

Section 2A.23—Median Opening Treatments for Divided Highways with Wide Medians

- The existing guidance language has been deleted due to the changes in the definition for intersection and median to eliminate the use of the 30-ft criterion for defining divided highway crossings as one or two intersections.
- There are numerous factors that establish the divided highway crossing as one or two intersections. Khazraee and Hawkins (2015, 2016) developed figures for guiding the decision for a limited number of conditions. Due to the number of factors that can impact the function of a divided highway crossing, it is not appropriate to add these figures to the MUTCD.
- This section has been revised to suggest treating the crossing as separate intersections when two conditions exist: left-turn paths cross, and there is adequate storage for the design vehicle.
  - Support language is also provided to indicate a general range for a median where it may be possible for the crossing to function as one or two intersections, depending upon the site-specific conditions.

Section 2B.32—KEEP RIGHT and KEEP LEFT Signs

- An option has been added as Paragraph 09a to allow the use of the sign in the median of a divided highway crossing that functions as a single intersection to make it consistent with the provisions of Section 2B.40—ONE WAY Signs. A support statement referencing Section 2B.40 has also been added (Paragraph 09b).

Section 2B.37—DO NOT ENTER Sign

- Paragraph 1 has been revised to incorporate changes approved by the NCUTCD in June 2013. Additional changes were made to this paragraph to make it consistent with the research suggestions for MUTCD changes.
- Researchers have revised the language in Paragraphs 2 and 5 to clarify that the suggested sign is the one placed on the right-hand side of a driver traveling on the wrong direction. The sign on the left side of the wrong-way driver is optional.
- Researchers have added asterisks to Figure 2B-12 to indicate the optional installation of the DO NOT ENTER sign, added the left-turn paths, added lane-use arrows (see Section 3B-20), and revised the figure title.
- Researchers have added a new Figure 2B-12a to address DO NOT ENTER signs at a single-intersection divided highway crossing. Left-turn paths do not cross in this new figure.

- Paragraph 05a, approved by the NCUTCD in June 2014, has been added. This allows the use of red light-emitting diodes (LEDs) in the DO NOT ENTER sign.

Section 2B.38—WRONG WAY Sign

- Guidance has been added as Paragraph 02a to indicate that the sign should be on the same side of the road as the DO NOT ENTER sign.
- Paragraph 03a, approved by the NCUTCD in June 2014, has been added. This allows the use of red LEDs in the WRONG WAY sign.
- Asterisks have been added to Figure 2B-12 to indicate the optional installation of the WRONG WAY signs.
- Researchers have added a new Figure 2B-12a to address WRONG WAY signs at a single-intersection divided highway crossing. Left-turn paths do not cross in this new figure.

Section 2B.40—ONE WAY Signs

- The language in Paragraphs 3, 4, and 5 has been revised to reflect the function of the crossing as one or two intersections rather than on the median width. The revised language in Paragraph 5 allows for the use of the optional far right ONE WAY sign at any divided highway intersection, regardless of median width/intersection function, to be consistent with how it is shown in Figure 2B-15.
- Figure 2B-15 has been revised to make it applicable to two separate intersections. Optional lane-use arrows (see Section 3B.20) and a second divided highway sign have been added. A note regarding the centerline in the median opening has also been added.
- Figure 2B-16 has been revised to make it applicable to a single intersection. The notes have been revised to indicate that the far right ONE WAY sign is optional even if only the other ONE WAY signs are used. The notes referencing other figures have also been revised. The reference to the median width distance has been removed. Optional lane-use arrows have been added (see Section 3B.20).
- The researchers suggested deletion of Figure 2B-17. With the elimination of the method of showing how to measure median width, this figure is the same as Figure 2B-16 except for the geometrics of the divided highway left-turn lanes. The traffic control devices shown in the two figures are the same.
- An option has been added as Paragraph 06a to allow the installation of ONE WAY signs at only one corner of the intersection of ramps and a crossroad. The language in Section 2B.41 where ONE WAY signs are required at only one corner conflicts with the language in 2B.40 where ONE WAY signs are required on the near right and far left corners.

Section 2B.40a—Wrong-Way Traffic Control at Divided Highway Crossings

- This is a new section that has been added to address the use of traffic control devices as a system to deter wrong-way movement at a divided highway intersection. Some of the language in this new section duplicates language in other sections (such as the rotation of the KEEP RIGHT sign). If this new section is added to the MUTCD, the researchers suggested deleting the duplicated language from the other sections.
- One of the challenges of adding this section is that it addresses the use of both signs and markings, even though the section is in Part 2. However, since Section 2B.41 also addresses pavement markings, the researchers felt comfortable addressing markings in this section.

Section 2B.41—Wrong-Way Traffic Control at Interchange Ramps

- Paragraph 1A requires ONE WAY signs at only one corner of the intersection, but Figure 2B-18 shows all ONE WAY signs as optional. The researchers have no research basis for indicating which ONE WAY signs are the optional signs.
- An option has been added to Paragraph 3 (Item F) to allow use of movement prohibition signs as indicated in Figure 2B-18.
- The reference in Paragraph 7 to Section 2B.41 has been changed to 2B.40a. When Section 2B.41 was in Chapter 2E in the 2003 MUTCD, this cross-reference was to the DO NOT ENTER sign section (2B.37). The cross-reference was lost in the publication of the 2009 MUTCD. With the addition of a new section on wrong-way traffic control at divided highway crossings (2B.40a), this reference has been changed from the DO NOT ENTER sign to the new section.

Section 2B.42—Divided Highway Crossing Signs

- The language in Paragraph 2 has been revised to reflect the function of the crossing as one or two intersections rather than on the median width. The language has also been revised to read better.

Section 3B.20—Pavement Word, Symbol, and Arrow Markings

- An option has been added as Paragraph 22a to specifically allow the use of lane-use arrows on the divided highway to deter wrong-way movement.
- The researchers have deleted the reference to Figure 2B-17 in Paragraph 23 since they are suggesting this figure be deleted. The figure could be moved to Section 3B.20 as an example of the use of lane-use arrows in offset left-turn lanes if desired.
- An option has been added as Paragraph 37a to allow the wrong-way arrow markings to be used in lieu of or in addition to lane-use arrows.

Additional Revisions

The additional changes listed below were necessitated by the elimination of the 30-ft criterion for distinguishing function as one or two intersections. The research team did a search for the term "median" and identified 229 occurrences of the term. Each of these was evaluated to determine if the use was affected by the removal of the 30-ft criterion for distinguishing between function as one or two intersections. Language in the following two sections was all that was identified as needing revisions (in addition to those already discussed above).

Section 2B.09—YIELD Sign Applications

- The reference to 30 ft in Item B of Paragraph 1 has been deleted. The text has been revised to reflect function as one or two intersections.

Section 4C.01—Studies and Factors for Justifying Traffic Control Signals

- The language in Paragraph 12 has been revised to delete reference to the width of the median and to simply state that a divided highway crossing that functions as two separate intersections should be considered as one intersection for the purpose of a signal warrant analysis.

Suggested Changes to MUTCD

Proposed additions are shown in blue underline, and proposed deletions are shown in ~~red strikethrough~~. Changes previously approved by NCUTCD, but not yet adopted by the Federal Highway Administration, are shown in green double underline for additions and ~~green double strikethrough~~ for deletions.

PART 1: GENERAL
CHAPTER 1A. GENERAL

Section 1A.13 Definitions of Headings, Words, and Phrases in this Manual

Standard:

When used in this Manual, the text headings of Standard, Guidance, Option, and Support shall be defined as follows:

94. Intersection—intersection is defined as follows:

(a) The area embraced within the prolongation or connection of the lateral curb lines, or if none, the lateral boundary lines of the roadways of two highways that join one another at, or approximately at, right angles, or the area within which vehicles traveling on different highways that join at any other angle might come into conflict.

(b) The junction of an alley or driveway with a roadway or highway shall not constitute an intersection, unless the roadway or highway at said junction is controlled by a traffic control device.

~~**(c) If a highway includes two roadways that are 30 feet or more apart (see definition of Median), then every crossing of each roadway of such divided highway by an intersecting highway shall be a separate intersection.**~~

(c) If a highway includes two roadways separated by a median, then every crossing of each roadway of such divided highway by an intersecting highway shall be a separate intersection if the opposing left-turn paths cross and there is sufficient interior storage for the design vehicle.

~~**(d) If both intersecting highways include two roadways that are 30 feet or more apart, then every crossing of any two roadways of such highways shall be a separate intersection.**~~

(d~~e~~) At a location controlled by a traffic control signal, regardless of the distance between the separate intersections as defined in (c) and (d) above:

(1) If a stop line, yield line, or crosswalk has not been designated on the roadway (within the median) between the separate intersections, the two intersections and the roadway (median) between them shall be considered as one intersection;

(2) Where a stop line, yield line, or crosswalk is designated on the roadway on the intersection approach, the area within the crosswalk and/or beyond the designated stop line or yield line shall be part of the intersection; and

(3) Where a crosswalk is designated on a roadway on the departure from the intersection, the intersection shall include the area extending to the far side of such crosswalk.

115. Median—the portion of a highway separating opposing directions of the traveled way ~~area between two roadways of a divided highway measured from edge of traveled way to edge of traveled way. The median excludes turn lanes. The median width might be different between intersections, interchanges, and at opposite approaches of the same intersection.~~

PART 2 SIGNS
CHAPTER 2A. GENERAL

Section 2A.23 Median Opening Treatments for Divided Highways ~~with Wide Medians~~

Guidance:

~~01 Where divided highways are separated by median widths at the median opening itself of 30 feet or more, median openings should be signed as two separate intersections.~~

01 A divided highway crossing should be signed and marked as separate intersections when both of the following conditions are present:

- *A. The paths of opposing left turns from the divided highway cross each other (see Figure A).*
- *B. There is adequate storage in the interior approaches for the types of vehicles expected to cross the divided highway.*

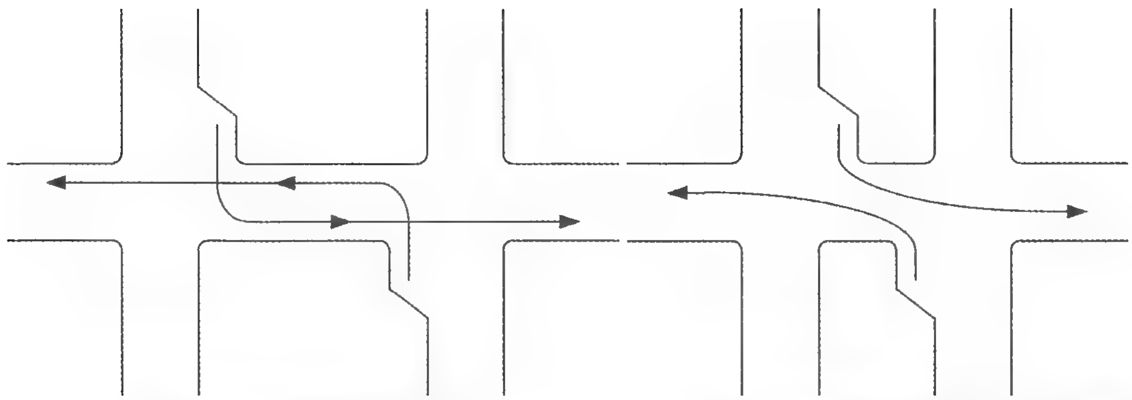
02 If both of the conditions in paragraph 2 do not exist, the divided highway crossing should be signed and marked as a single intersection.

03 At the crossing of two divided highways, engineering judgement should be used to determine the number of separate intersections.

Support:

04 Research has indicated that median widths (including left-turn lanes) less than 30 ft typically function as a single intersection and that median widths greater than 85 ft typically function as two intersections. Divided highway crossings with median widths between 30 and 85 ft can function as one or two intersections depending upon the geometric design of the divided highway crossing. Factors that impact the function of a crossing as a single intersection or multiple intersections include the left-turn paths, the interior storage, the offset of the opposing left-turn lanes, the length of the median opening (measured parallel to the centerline of the divided highway), and the geometric design of the median noses.

[Add Figure A to define left-turn paths.]



a. Opposing Paths Cross. **b. Opposing Paths Do Not Cross.**

Figure A. Types of Left-Turn Paths at a Divided Highway Crossing.

PART 2 SIGNS
CHAPTER 2B. REGULATORY SIGNS, BARRICADES, AND GATES

Section 2B.32 <u>Keep Right and Keep Left Signs (R4-7, R4-8)</u>

Option:

01 The Keep Right (R4-7) sign (see Figure 2B-10) may be used at locations where it is necessary for traffic to pass only to the right-hand side of a roadway feature or obstruction. The Keep Left (R4-8) sign (see Figure 2B-10) may be used at locations where it is necessary for traffic to pass only to the left-hand side of a roadway feature or obstruction.

Guidance:

02 *At locations where it is not readily apparent that traffic is required to keep to the right, a Keep Right sign should be used.*

03 *If used, the Keep Right sign should be installed as close as practical to approach ends of raised medians, parkways, islands, and underpass piers. The sign should be mounted on the face of or just in front of a pier or other obstruction separating opposite directions of traffic in the center of the highway such that traffic will have to pass to the right-hand side of the sign.*

Standard:

04 The Keep Right sign shall not be installed on the right-hand side of the roadway in a position where traffic must pass to the left-hand side of the sign.

Option:

05 The Keep Right sign may be omitted at intermediate ends of divisional islands and medians.

06 Word message KEEP RIGHT (LEFT) with an arrow (R4-7a or R4-7b) signs (see Figure 2B-10) may be used instead of the R4-7 or R4-8 symbol signs.

07 Where the obstruction obscures the Keep Right sign, the minimum placement height may be increased for better sign visibility.

08 A narrow Keep Right (R4-7c) sign (see Figure 2B-10) may be installed on the approach end of a median island that is less than 4 feet wide at the point where the sign is to be located.

Standard:

09 A narrow Keep Right (R4-7c) sign shall not be installed on a median island that has a width of 4 feet or more at the point where the sign is to be located.

Option:

09a The Keep Right sign may be installed in the median of a divided highway crossing that functions as a single intersection such that it is visible to traffic on the divided highway and the crossroad approach.

Support

09b Section 2B.40 provides more information about the use of the Keep Right sign in combination with or in lieu of One Way signs at divided highway crossings.

Section 2B.37 DO NOT ENTER Sign (R5-1)

Standard:

01 **The DO NOT ENTER (R5-1) sign (see Figure 2B-11) shall be used where ~~traffic is prohibited~~ a two-way roadway becomes a one-way roadway as shown in Figure 2B-14, at divided highway crossings as shown in Figures 2B-12 and 2B-12a (see Section 2B.40a), and near the downstream end of an Interchange exit ramp as shown in Figure 2B-18 (see Section 2B.41).~~from entering a restricted roadway.~~** [Note: Approved by NCUTCD on 6-28-13.]

Guidance:

02 *The DO NOT ENTER sign, if used, should be placed directly in view of a road user at the point where a road user could wrongly enter a divided highway, one-way roadway, or ramp ~~(see Figure 2B-12)~~. The sign should be mounted on the right-hand side of a road user traveling in the wrong direction on the roadway, ~~facing traffic that might enter the roadway or ramp in the wrong direction~~.*

03 *If the DO NOT ENTER sign would be visible to traffic to which it does not apply, the sign should be turned away from, or shielded from, the view of that traffic.*

Option:

04 The DO NOT ENTER sign may be installed where it is necessary to emphasize the one-way traffic movement on a ramp or turning lane.

05 A second DO NOT ENTER sign may be used on the left-hand side of a road user traveling in the wrong direction on the roadway ~~may be used~~, particularly where traffic approaches from an intersecting roadway ~~(see Figure 2B-12)~~.

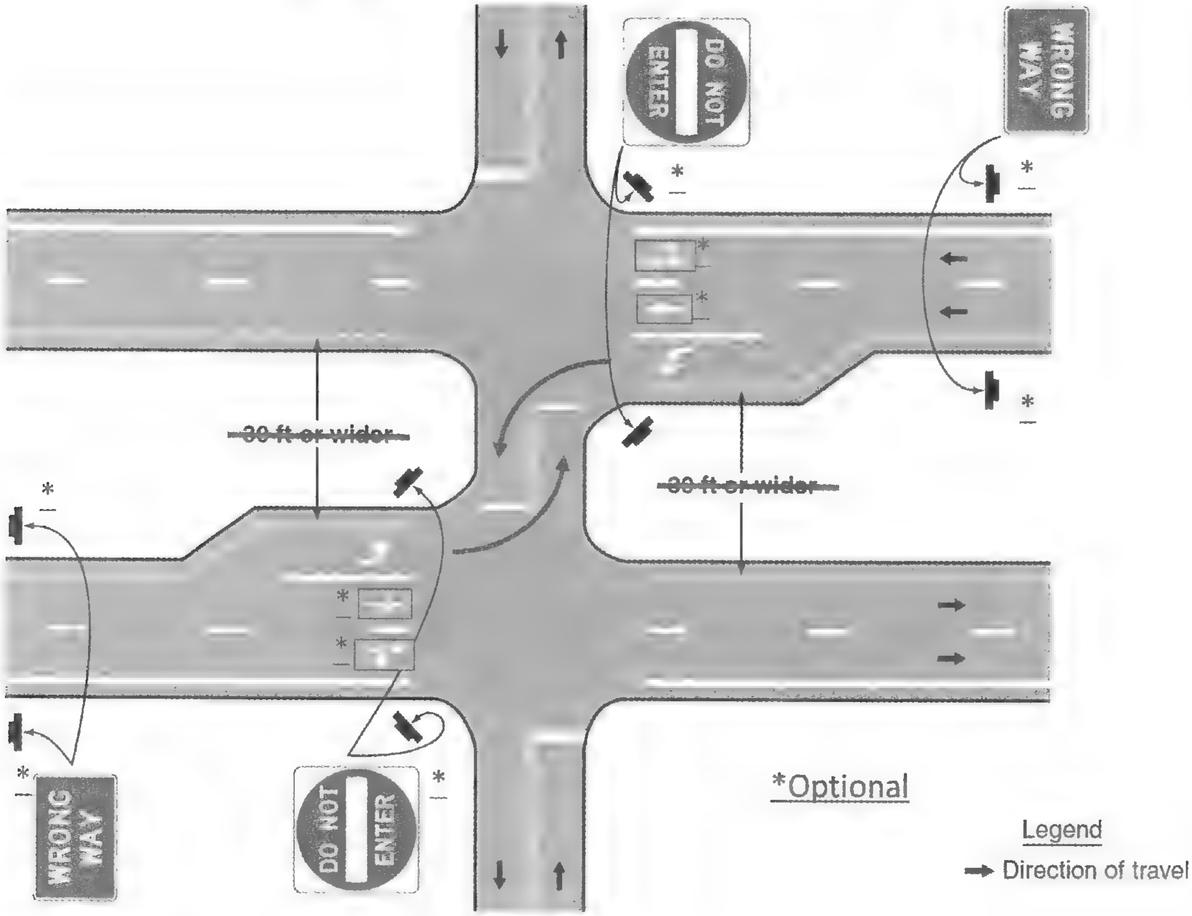
05a Red LEDs may be installed within the border of the DO NOT ENTER sign to enhance the conspicuity of the sign. The LEDs may be vehicle actuated to flash at the rates as shown in Section 2A.07 (paragraph 09). [Note: Approved by NCUTCD on 6/28/2014.]

Support:

06 Section 2B.41 contains information regarding an optional lower mounting height for DO NOT ENTER signs that are located along an exit ramp facing a road user who is traveling in the wrong direction.

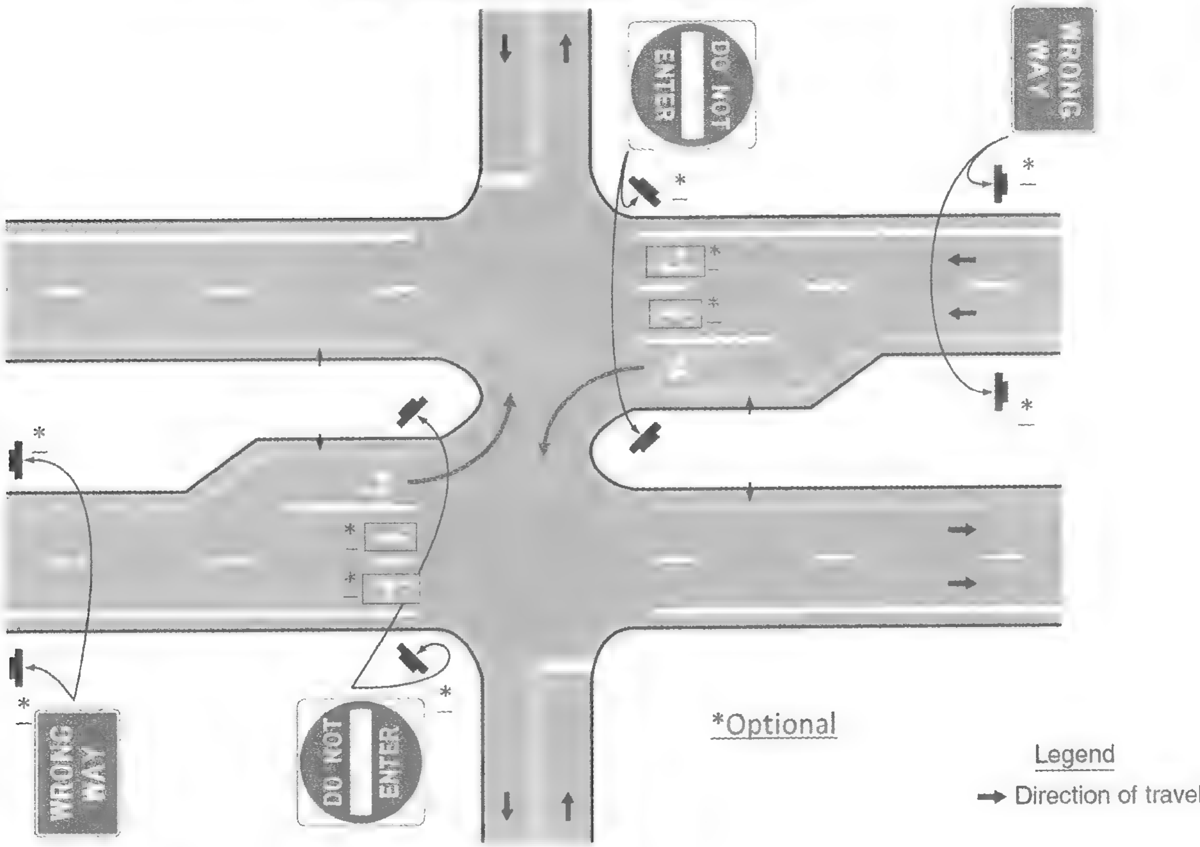
[Revise Figure 2B-12 as shown.]

Figure 2B-12. Locations of Wrong Way Signing for Divided Highways that Function as Separate Intersections



[Add Figure 2B-12a to address DO NOT ENTER signs for single intersection.]

Figure 2B-12a. Locations of Wrong Way Signing for Divided Highways that Function as a Single Intersection



Section 2B.38 WRONG WAY Sign (R5-1a)

Option:

01 The WRONG WAY (R5-1a) sign (see Figure 2B-11) may be used as a supplement to the DO NOT ENTER sign where an exit ramp intersects a crossroad or a crossroad intersects a one-way roadway in a manner that does not physically discourage or prevent wrong-way entry (see Figure 2B-12).

Guidance:

02 *If used, the WRONG WAY sign should be placed at a location along the exit ramp or the one-way roadway farther from the crossroad than the DO NOT ENTER sign (see Sections 2B.40a and ~~Section~~ 2B.41).*

02a *The WRONG WAY sign should be placed on the same side of the road as the DO NOT ENTER sign.*

Support:

03 Section 2B.41 contains information regarding an optional lower mounting height for WRONG WAY signs that are located along an exit ramp facing a road user who is traveling in the wrong direction.

03a Red LEDs may be installed within the border of the WRONG WAY sign to enhance the conspicuity of the sign. The LEDs may be vehicle actuated to flash at the rates as shown in Section 2A.07(09). [Note: Approved by NCUTCD on 6/28/2014.]

Section 2B.40 ONE WAY Signs (R6-1, R6-2)

Standard:

01 Except as provided in Paragraph 6, the ONE WAY (R6-1 or R6-2) sign (see Figure 2B-13) shall be used to indicate streets or roadways upon which vehicular traffic is allowed to travel in one direction only.

02 ONE WAY signs shall be placed parallel to the one-way street at all alleys and roadways that intersect one-way roadways as shown in Figure 2B-14.

03 At the crossing of a roadway with a divided highway that functions as separate intersections, ~~At an intersection with a divided highway that has a median width at the intersection itself of 30 feet or more,~~ ONE WAY signs shall be placed, visible to each crossroad approach, on the near right and far left corners of each intersection with the directional roadways (see Figure 2B-15).

04 At the crossing of a roadway with a divided highway that functions as a single intersection, ~~At an intersection with a divided highway that has a median width at the intersection itself of less than 30 feet,~~ Keep Right (R4-7) signs and/or ONE WAY signs shall be installed (see Figures 2B-16 ~~and 2B-17~~). If Keep Right signs are installed, they shall be placed as close as practical to the approach ends of the medians and shall be visible to traffic on the divided highway and the applicable ~~each~~ crossroad approach. If ONE WAY signs are installed, they shall be placed on the near right and far left corners of the intersection and shall be visible to each crossroad approach.

Option:

05 **At the crossing of a roadway with a divided highway, regardless of function as a single or separate intersections,** ~~At an intersection with a divided highway that has a median width at the intersection itself of less than 30 feet,~~ ONE WAY signs may also be placed on the far right corner of the intersection as shown in Figures 2B-15 and 2B-16 ~~and 2B-17~~.

06 ONE WAY signs may be omitted on the one-way roadways of divided highways, where the design of interchanges indicates the direction of traffic on the separate roadways.

06a ONE WAY signs may be omitted from one corner of the intersection of a crossroad with a interchange ramp (see Section 2B.41).

Standard:

07 If used at unsignalized intersections with one-way streets, ONE WAY signs shall be placed on the near right and the far left corners of the intersection facing traffic entering or crossing the one-way street (see Figure 2B-14).

08 If used at signalized intersections with one-way streets, ONE WAY signs shall be placed near the appropriate signal faces, on the poles holding the traffic signals, on the mast arm or span wire holding the signals, or at the locations specified for unsignalized intersections.

09 At unsignalized T-intersections where the roadway at the top of the T-intersection is a one-way roadway, ONE WAY signs shall be placed on the near right and the far side of the intersection facing traffic on the stem approach (see Figure 2B-14).

10 At signalized T-intersections where the roadway at the top of the T-intersection is a one-way roadway, ONE WAY signs shall be placed near the appropriate signal faces, on the poles holding the traffic signals, on the mast arm or span wire holding the signals, or at the locations specified for unsignalized intersections.

Option:

11 Where the central island of a roundabout allows for the installation of signs, ONE WAY signs may be used instead of or in addition to Roundabout Directional Arrow (R6-4 series) signs (see Section 2B.43) to direct traffic counter-clockwise around the central island.

Guidance:

12 *Where used on the central island of a roundabout, the mounting height of a ONE WAY sign should be at least 4 feet, measured vertically from the bottom of the sign to the elevation of the near edge of the traveled way.*

Support:

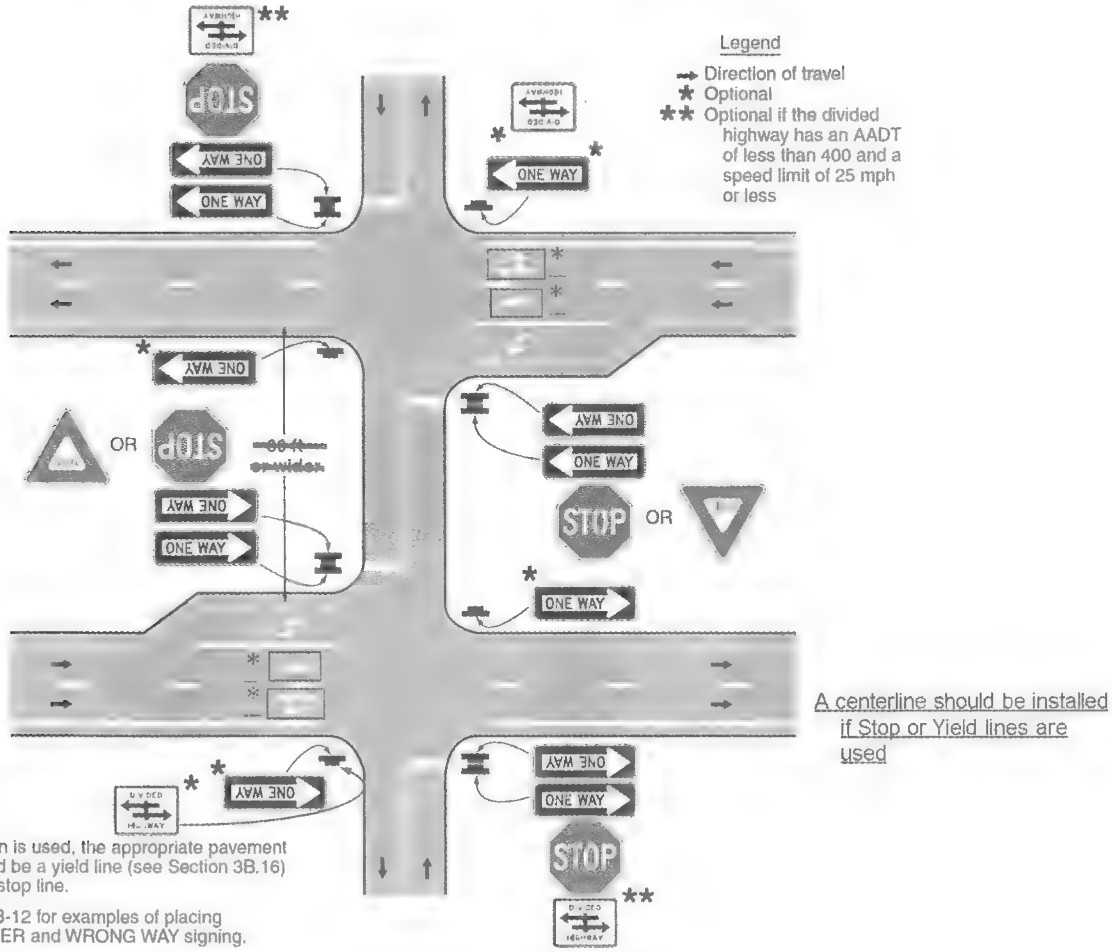
13 Using ONE WAY signs on the central island of a roundabout might result in some drivers incorrectly concluding that the cross street is a one-way street. Using Roundabout Directional Arrow signs might reduce this confusion. However, using ONE WAY signs might be necessary in States that have defined a roundabout as a series of T-intersections.

Option:

14 The BEGIN ONE WAY (R6-6) sign (see Figure 2B-13) may be used notify road users of the beginning point of a one direction of travel restriction on the street or roadway. The END ONE WAY (R6-7) sign (see Figure 2B-13) may be used notify road users of the ending point of a one direction of travel restriction on the street or roadway.

[Revise Figures 2B-15 and 16 as shown.]

Figure 2B-15. ONE WAY Signing for Divided Highways
that Function as Separate Intersections

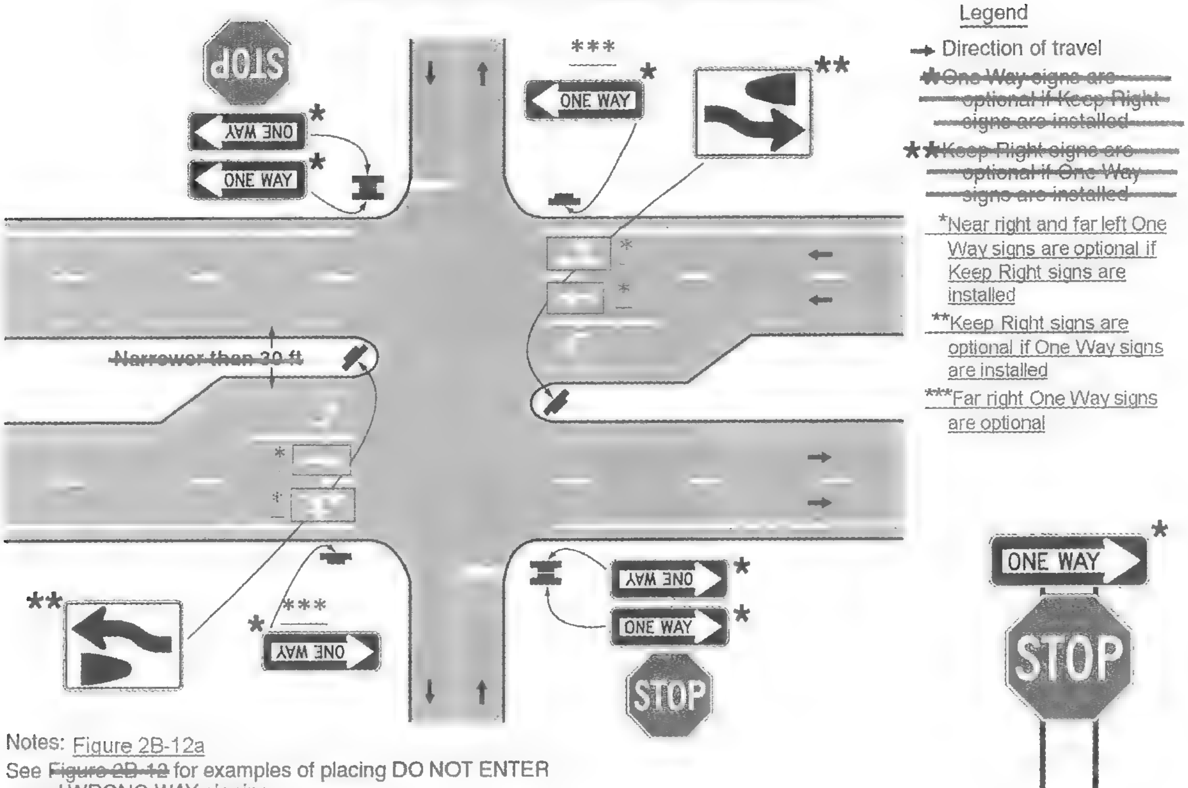


Notes:

If a YIELD sign is used, the appropriate pavement marking would be a yield line (see Section 3B.16) rather than a stop line.

See Figure 2B-12 for examples of placing DO NOT ENTER and WRONG WAY signing.

Figure 2B-16. ONE WAY Signing for Divided Highways
that Function as a Single Intersection



Notes: Figure 2B-12a
See ~~Figure 2B-12~~ for examples of placing DO NOT ENTER and WRONG WAY signing.
~~See Figure 2B-15 if median is 30 feet or more in width.~~

Section 2B.40a Wrong-Way Traffic Control at Divided Highway Crossings

Support:

01 At the crossing of a divided highway with a roadway, the type and location of traffic control devices used to deter wrong-way movements depend upon the classification of the crossing as a single intersection or two intersections (see Section 2A.23).

Standard:

02 **When a divided highway crossing functions as a single intersection, the following traffic control devices shall be used to deter wrong-way movements:**

A. **ONE WAY signs shall be installed on the near right and far left corners of the intersection (see Figure 2B-16).**
B. **A DO NOT ENTER sign shall be installed on the median side of the roadway (the right-hand side of a road user traveling in the wrong direction) (See Figure 2B-12a).**
C. **A centerline marking shall not be installed in the median portion of the crossroad when the divided highway crossing functions as a single intersection.**

Option:

03 When a divided highway crossing functions as a single intersection, the following traffic control devices may be used to deter wrong-way movements:

A. A DO NOT ENTER sign may be installed on the left-hand side of a road user traveling in the wrong direction.

B. A WRONG WAY sign may be used to supplement any DO NOT ENTER signs (see Section 2B.38) (see Section 2B.37).
C. A KEEP RIGHT sign may be installed in the median in lieu of, or as a supplement to, the required ONE WAY signs.
D. Lane-use arrows may be used on the through lanes of the divided highway near the crossroad (see Section 3B.20). Wrong-way arrow markings may be used in a through or shared-use lane upstream of the intersection (see Section 3B.20).

Guidance:

04 *If used in the median of a divided highway crossing, the KEEP RIGHT sign shall be oriented so that it is visible to traffic on the divided highway and the applicable crossroad approach.*

Standard:

05 **When a divided highway crossing functions as two separate intersections, the following traffic control devices shall be used to deter wrong-way movements:**

A. **ONE WAY signs shall be installed on the near right and far left corners of each intersection (see Figure 2B-15).**
B. **A DO NOT ENTER sign shall be installed on the median side of the roadway (the right-hand side of a road user traveling in the wrong direction) (see Figure 2B-12).**
C. **A STOP or YIELD sign shall be installed on the interior approaches (median portion of the crossroad).**

Guidance:

06 *When a divided highway crossing functions as two separate intersections, the following traffic control devices should be used to deter wrong-way movements:*

A. *Where Stop or Yield lines are provided on the interior approaches, a centerline marking should be installed between the Stop or Yield lines on each interior approach.*

Option:

07 When a divided highway crossing functions as two separate intersections, the following traffic control devices may be used to deter wrong-way movements:

A. A DO NOT ENTER sign may be installed on the left-hand side of a road user traveling in the wrong direction (see Section 2B.37).
B. A WRONG WAY sign may be used to supplement any DO NOT ENTER sign (see Section 2B.38).
C. Lane-use arrows may be used on the through lanes of the divided highway near the crossroad (see Section 3B.20). Wrong-way arrow markings may be used in a through or shared-use lane upstream of the intersection (see Section 3B.20).
D. Stop or Yield lines may be used on the interior approaches (see Section 3B.16).

Section 2B.41 Wrong-Way Traffic Control at Interchange Ramps

Standard:

01 At interchange exit ramp terminals where the ramp intersects a crossroad in such a manner that wrong-way entry could inadvertently be made, the following signs shall be used (see Figure 2B-18):

A. **At least one ONE WAY sign for each direction of travel on the crossroad shall be placed where the exit ramp intersects the crossroad.**

B. At least one DO NOT ENTER sign shall be conspicuously placed near the downstream end of the exit ramp in positions appropriate for full view of a road user starting to enter wrongly from the crossroad.

C. At least one WRONG WAY sign shall be placed on the exit ramp facing a road user traveling in the wrong direction.

Guidance:

02 In addition, the following pavement markings should be used (see Figure 2B-18):

A. On two-lane paved crossroads at interchanges, double solid yellow lines should be used as a center line for an adequate distance on both sides approaching the ramp intersections.

B. Where crossroad channelization or ramp geometrics do not make wrong-way movements difficult, a lane-use arrow should be placed in each lane of an exit ramp near the crossroad terminal where it will be clearly visible to a potential wrong-way road user.

Option:

03 The following traffic control devices may be used to supplement the signs and pavement markings described in Paragraphs 1 and 2:

A. Additional ONE WAY signs may be placed, especially on two-lane rural crossroads, appropriately in advance of the ramp intersection to supplement the required ONE WAY sign(s).

B. Additional WRONG WAY signs may be used.

C. Slender, elongated wrong-way arrow pavement markings (see Figure 3B-24) intended primarily to warn wrong-way road users that they are traveling in the wrong direction may be placed upstream from the ramp terminus (see Figure 2B-18) to indicate the correct direction of traffic flow. Wrong-way arrow pavement markings may also be placed on the exit ramp at appropriate locations near the crossroad junction to indicate wrong-way movement. The wrong-way arrow markings may consist of pavement markings or bidirectional red-and-white raised pavement markers or other units that show red to wrong-way road users and white to other road users (see Figure 3B-24).

D. Lane-use arrow pavement markings may be placed on the exit ramp and crossroad near their intersection to indicate the permissive direction of flow.

E. Freeway entrance signs (see Section 2D.46) may be used.

F. Movement prohibition signs may be used on the approaches to the exit ramp.

Guidance:

04 On interchange entrance ramps where the ramp merges with the through roadway and the design of the interchange does not clearly make evident the direction of traffic on the separate roadways or ramps, a ONE WAY sign visible to traffic on the entrance ramp and through roadway should be placed on each side of the through roadway near the entrance ramp merging point as illustrated in Figure 2B-19.

Option:

05 At locations where engineering judgment determines that a special need exists, other standard warning or prohibitive methods and devices may be used as a deterrent to the wrong-way movement.

06 Where there are no parked cars, pedestrian activity or other obstructions such as snow or vegetation, and if an engineering study indicates that a lower mounting height would address

wrong-way movements on freeway or expressway exit ramps, a DO NOT ENTER sign(s) and/or a WRONG WAY sign(s) that is located along the exit ramp facing a road user who is traveling in the wrong direction may be installed at a minimum mounting height of 3 feet, measured vertically from the bottom of the sign to the elevation of the near edge of the pavement.

Support:

07 Section 2B.40a ~~2B.41~~ contains further information on signing to avoid wrong-way movements at at-grade intersections on expressways.

Section 2B.42 Divided Highway Crossing Signs (R6-3, R6-3a)

Standard:

01 On unsignalized minor-street approaches from which both left turns and right turns are permitted onto a divided highway that has a median width at the intersection itself of 30 feet or more, except as provided in Paragraph 2, a Divided Highway Crossing (R6-3 or R6-3a) sign (see Figure 2B-13) shall be used to advise road users that they are approaching an intersection with a divided highway (see Figure 2B-15).

Option:

02 If a divided highway ~~that has a median width at the intersection itself of 30 feet or more~~ crossing functions as separate intersections (see Section 2A.23) and meets both of the following criteria, the Divided Highway Crossing signs facing the unsignalized minor-street approaches may be omitted.

A. Traffic volume on the cross road of less than 400 AADT.
B. Speed limit on the cross road of 25 mph or less.

03 A Divided Highway Crossing sign may be used on signalized minor-street approaches from which both left turns and right turns are permitted onto a divided highway to advise road users that they are approaching an intersection with a divided highway.

Standard:

04 If a Divided Highway Crossing sign is used at a four-legged intersection, the R6-3 sign shall be used. If used at a T-intersection, the R6-3a sign shall be used.

05 The Divided Highway Crossing sign shall be located on the near right corner of the intersection, mounted beneath a STOP or YIELD sign or on a separate support.

Option:

06 An additional Divided Highway Crossing sign may be installed on the left-hand side of the approach to supplement the Divided Highway Crossing sign on the near right corner of the intersection.

PART 3 MARKINGS
CHAPTER 3B. PAVEMENT AND CURB MARKINGS

Section 3B.20 <u>Pavement Word, Symbol, and Arrow Markings</u>

Support:

01 Word, symbol, and arrow markings on the pavement are used for the purpose of guiding, warning, or regulating traffic. These pavement markings can be helpful to road users in some locations by supplementing signs and providing additional emphasis for important regulatory, warning, or guidance messages, because the markings do not require diversion of the road user's attention from the roadway surface. Symbol messages are preferable to word messages. Examples of standard word and arrow pavement markings are shown in Figures 3B-23 and 3B-24.

Option:

02 Word, symbol, and arrow markings, including those contained in the "Standard Highway Signs and Markings" book (see Section 1A.11), may be used as determined by engineering judgment to supplement signs and/or to provide additional emphasis for regulatory, warning, or guidance messages. Among the word, symbol, and arrow markings that may be used are the following:

A. Regulatory:
   1. STOP
   2. YIELD
   3. RIGHT (LEFT) TURN ONLY
   4. 25 MPH
   5. Lane-use and wrong-way arrows
   6. Diamond symbol for HOV lanes
   7. Other preferential lane word markings

B. Warning:
   1. STOP AHEAD
   2. YIELD AHEAD
   3. YIELD AHEAD triangle symbol
   4. SCHOOL XING
   5. SIGNAL AHEAD
   6. PED XING
   7. SCHOOL
   8. R X R
   9. BUMP
   10. HUMP
   11. Lane-reduction arrows

C. Guide:
   1. Route numbers (route shield pavement marking symbols and/or words such as I-81, US 40, STATE 135, or ROUTE 10)
   2. Cardinal directions (NORTH, SOUTH, EAST, or WEST)
   3. TO
   4. Destination names or abbreviations thereof

Standard:

03 Word, symbol, and arrow markings shall be white, except as otherwise provided in this Section.

04 Pavement marking letters, numerals, symbols, and arrows shall be installed in accordance with the design details in the Pavement Markings chapter of the "Standard Highway Signs and Markings" book (see Section 1A.11).

Guidance:

05 Letters and numerals should be 6 feet or more in height.

06 Word and symbol markings should not exceed three lines of information.

07 If a pavement marking word message consists of more than one line of information, it should read in the direction of travel. The first word of the message should be nearest to the road user.

08 Except for the two opposing arrows of a two-way left-turn lane marking (see Figure 3B-7), the longitudinal space between word or symbol message markings, including arrow markings, should be at least four times the height of the characters for low-speed roads, but not more than ten times the height of the characters under any conditions.

09 The number of different word and symbol markings used should be minimized to provide effective guidance and avoid misunderstanding.

10 Except for the SCHOOL word marking (see Section 7C.03), pavement word, symbol, and arrow markings should be no more than one lane in width.

11 Pavement word, symbol, and arrow markings should be proportionally scaled to fit within the width of the facility upon which they are applied.

Option:

12 On narrow, low-speed shared-use paths, the pavement words, symbols, and arrows may be smaller than suggested, but to the relative scale.

13 Pavement markings simulating Interstate, U.S., State, and other official highway route shield signs (see Figure 2D-3) with appropriate route numbers, but elongated for proper proportioning when viewed as a marking, may be used to guide road users to their destinations (see Figure 3B-25).

Standard:

14 Except at the ends of aisles in parking lots, the word STOP shall not be used on the pavement unless accompanied by a stop line (see Section 3B.16) and STOP sign (see Section 2B.05). At the ends of aisles in parking lots, the word STOP shall not be used on the pavement unless accompanied by a stop line.

15 The word STOP shall not be placed on the pavement in advance of a stop line, unless every vehicle is required to stop at all times.

Option:

16 A yield-ahead triangle symbol (see Figure 3B-26) or YIELD AHEAD word pavement marking may be used on approaches to intersections where the approaching traffic will encounter a YIELD sign at the intersection.

Standard:

17 The yield-ahead triangle symbol or YIELD AHEAD word pavement marking shall not be used unless a YIELD sign (see Section 2B.08) is in place at the intersection. The yield-ahead symbol marking shall be as shown in Figure 3B-26.

Guidance:

18 The International Symbol of Accessibility parking space marking (see Figure 3B-22) should be placed in each parking space designated for use by persons with disabilities.

Option:

19 A blue background with white border may supplement the wheelchair symbol as shown in Figure 3B-22.

Support:

20 Lane-use arrow markings (see Figure 3B-24) are used to indicate the mandatory or permissible movements in certain lanes (see Figure 3B-27) and in two-way left-turn lanes (see Figure 3B-7).

Guidance:

21 Lane-use arrow markings (see Figure 3B-24) should be used in lanes designated for the exclusive use of a turning movement, including turn bays, except where engineering judgment determines that physical conditions or other markings (such as a dotted extension of the lane line through the taper into the turn bay) clearly discourage unintentional use of a turn bay by through vehicles. Lane-use arrow markings should also be used in lanes from which movements are allowed that are contrary to the normal rules of the road (see Drawing B of Figure 3B-13). When used in turn lanes, at least two arrows should be used, one at or near the upstream end of the full-width turn lane and one an appropriate distance upstream from the stop line or intersection (see Drawing A of Figure 3B-11).

Option:

22 An additional arrow or arrows may be used in a turn lane. When arrows are used for a short turn lane, the second (downstream) arrow may be omitted based on engineering judgment.

22a Lane-use arrows may be used in the lanes of a divided highway to deter wrong-way movements at the crossing of the divided highway with a crossroad (see Figures 2B-15 and 2B-16).

Guidance:

23 Where opposing offset channelized left-turn lanes exist, lane-use arrow markings should be placed near the downstream terminus of the offset left-turn lanes to reduce wrong-way movements ~~(see Figure 2B-17)~~.

Support:

24 An arrow at the downstream end of a turn lane can help to prevent wrong way movements.

Standard:

25 Where through lanes approaching an intersection become mandatory turn lanes, lane-use arrow markings (see Figure 3B-24) shall be used and shall be accompanied by standard signs.

Guidance:

26 Where through lanes approaching an intersection become mandatory turn lanes, ONLY word markings (see Figure 3B-23) should be used in addition to the required lane-use arrow markings and signs (see Sections 2B.19 and 2B.20). These markings and signs should be placed well in advance of the turn and should be repeated as necessary to prevent entrapment and to help the road user select the appropriate lane in advance of reaching a queue of waiting vehicles (see Drawing A of Figure 3B-11).

Option:

27 On freeways or expressways where a through lane becomes a mandatory exit lane, lane-use arrow markings may be used on the approach to the exit in the dropped lane and in an adjacent optional through-or-exit lane if one exists.

Guidance:

28 A two-way left-turn lane-use arrow pavement marking, with opposing arrows spaced as shown in Figure 3B-7, should be used at or just downstream from the beginning of a two-way left-turn lane.

Option:

29 Additional two-way left-turn lane-use arrow markings may be used at other locations along a two-way left-turn lane where engineering judgment determines that such additional markings are needed to emphasize the proper use of the lane.

Standard:

30 A single-direction lane-use arrow shall not be used in a lane bordered on both sides by yellow two-way left-turn lane longitudinal markings.

31 Lane-use, lane-reduction, and wrong-way arrow markings shall be designed as shown in Figure 3B-24 and in the "Standard Highway Signs and Markings" book (see Section 1A.11).

Option:

32 The ONLY word marking (see Figure 3B-23) may be used to supplement the lane-use arrow markings in lanes that are designated for the exclusive use of a single movement (see Figure 3B-27) or to supplement a preferential lane word or symbol marking (see Section 3D.01).

Standard:

33 The ONLY word marking shall not be used in a lane that is shared by more than one movement.

Guidance:

34 Where a lane-reduction transition occurs on a roadway with a speed limit of 45 mph or more, the lane-reduction arrow markings shown in Drawing F in Figure 3B-24 should be used (see Figure 3B-14). Except for acceleration lanes, where a lane-reduction transition occurs on a roadway with a speed limit of less than 45 mph, the lane-reduction arrow markings shown in Drawing F in Figure 3B-24 should be used if determined to be appropriate based on engineering judgment.

Option:

35 Lane-reduction arrow markings may be used in long acceleration lanes based on engineering judgment.

Guidance:

36 Where crossroad channelization or ramp geometrics do not make wrong-way movements difficult, the appropriate lane-use arrow should be placed in each lane of an exit ramp near the crossroad terminal where it will be clearly visible to a potential wrong-way road user (see Figure 2B-18).

Option:

37 The wrong-way arrow markings shown in Drawing D in Figure 3B-24 may be placed near the downstream terminus of a ramp as shown in Figures 2B-18 and 2B-19, or at other locations where lane-use arrows are not appropriate, to indicate the correct direction of traffic flow and to discourage drivers from traveling in the wrong direction.

37a The wrong-way arrow marking may be used upstream of the intersection at a divided highway crossing to deter wrong-way movements. They may be used in lieu of or in addition to lane-use arrows.

Section 2B.09 YIELD Sign Applications

Option:

01 YIELD signs may be installed:

A. On the approaches to a through street or highway where conditions are such that a full stop is not always required.
B. At the second intersection ~~crossroad~~ of a divided highway crossing or median break functioning as two separate intersections~~, where the median width at the intersection is 30 feet or greater~~. In this case, a STOP or YIELD sign may be installed at the entrance to the first intersection ~~roadway~~ of a divided highway crossing, and a YIELD sign may be installed at the entrance to the second intersection ~~roadway~~.
C. For a channelized turn lane that is separated from the adjacent travel lanes by an island, even if the adjacent lanes at the intersection are controlled by a highway traffic control signal or by a STOP sign.
D. At an intersection where a special problem exists and where engineering judgment indicates the problem to be susceptible to correction by the use of the YIELD sign.
E. Facing the entering roadway for a merge-type movement if engineering judgment indicates that control is needed because acceleration geometry and/or sight distance is not adequate for merging traffic operation.

Standard:

02 A YIELD (R1-2) sign shall be used to assign right-of-way at the entrance to a roundabout. YIELD signs at roundabouts shall be used to control the approach roadways and shall not be used to control the circulatory roadway.

03 Other than for all of the approaches to a roundabout, YIELD signs shall not be placed on all of the approaches to an intersection.

Section 4C.01 <u>Studies and Factors for Justifying Traffic Control Signals</u>

Standard:

01 An engineering study of traffic conditions, pedestrian characteristics, and physical characteristics of the location shall be performed to determine whether installation of a traffic control signal is justified at a particular location.

02 The investigation of the need for a traffic control signal shall include an analysis of factors related to the existing operation and safety at the study location and the potential to improve these conditions, and the applicable factors contained in the following traffic signal warrants:

Warrant 1, Eight-Hour Vehicular Volume
Warrant 2, Four-Hour Vehicular Volume
Warrant 3, Peak Hour
Warrant 4, Pedestrian Volume
Warrant 5, School Crossing
Warrant 6, Coordinated Signal System
Warrant 7, Crash Experience
Warrant 8, Roadway Network
Warrant 9, Intersection Near a Grade Crossing

03 The satisfaction of a traffic signal warrant or warrants shall not in itself require the installation of a traffic control signal.

Support:

04 Sections 8C.09 and 8C.10 contain information regarding the use of traffic control signals instead of gates and/or flashing-light signals at highway-rail grade crossings and highway-light rail transit grade crossings, respectively.

Guidance:

05 A traffic control signal should not be installed unless one or more of the factors described in this Chapter are met.

06 A traffic control signal should not be installed unless an engineering study indicates that installing a traffic control signal will improve the overall safety and/or operation of the intersection.

07 A traffic control signal should not be installed if it will seriously disrupt progressive traffic flow.

08 The study should consider the effects of the right-turn vehicles from the minor-street approaches. Engineering judgment should be used to determine what, if any, portion of the right-turn traffic is subtracted from the minor-street traffic count when evaluating the count against the signal warrants listed in Paragraph 2.

09 Engineering judgment should also be used in applying various traffic signal warrants to cases where approaches consist of one lane plus one left-turn or right-turn lane. The site-specific traffic characteristics should dictate whether an approach is considered as one lane or two lanes. For example, for an approach with one lane for through and right-turning traffic plus a left-turn lane, if engineering judgment indicates that it should be considered a one-lane approach because the traffic using the left-turn lane is minor, the total traffic volume approaching the intersection should be applied against the signal warrants as a one-lane approach. The approach should be considered two lanes if approximately half of the traffic on

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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